THE ROLE OF BIODIVERSITY IN AGRONOMY

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I. INTRODUCTION

Human beings, originally children of nature representing one species among the many sharing a small portion of the terrestrial environment, have gradually increased in numbers and expanded the extent and range of their activity, eventually gaining dominance over, and drastically modifying, often for food production, entire terrestrial and even marine biomes throughout the world. Consequently, numerous other species have been deprived of their natural habitats, endangered, or even eradicated. Recent calculations suggest that rates of species extinctions are now on the order of 100 to 1000 times those before humans dominated the Earth. For some

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well-documented groups, extinctions are even greater. Over the past two thousand years, humans have driven to extinction as many as one-quarter of Earth's bird species (Steadman, 1995). Unless checked, the continued increase of human population and the intensified manipulation of the environment for short-term advantage threaten to turn human success into eventual failure. Having tampered with nature in hopes of gaining control over it, humans are actually more dependent than ever on its complex workings, in which the diversity and intrinsic mutuality of all life forms are essential factors.

A crucial imperative is to ensure the adequate production and supply of food for a growing population in a world in which biotic, terrestrial, and aquatic resources have already been seriously degraded or depleted. Despite the lower fertility levels projected and the increased mortality risks to which some populations are being subjected, the population of the world is expected to increase by some 3 billion in the coming decades, from the current 6.3 billion to a total of some 9 billion before it stabilizes (United Nations Population Division, 2003). The yearly addition of an estimated 70–80 million people will impose greater demands for food, housing, health, education, political organization, public order, and employment. The world's average population density of 45 people/km^2 is projected to rise to 66 people/km^2 by 2050. Since only about 10% of land is arable, population densities per unit of arable land are roughly 10 times higher (Cohen, 2003). Given the poverty and famine that prevail in several regions, and the foreseen change of the earth's climate (which is inherently unstable in any case), it is an open question whether, and how, humanity can provide for itself while avoiding irreversible damage to natural ecosystems and their biodiversity. Increasing awareness of the issue and the development of modern methods of conservation management offer hope for some progress in this difficult task. Utilizing the promise inherent in such methods must, however, be constrained by an understanding of the potential problems and hazards they pose (Hillel *et al*., 2002).

II. HISTORICAL BACKGROUND

For the greater part of their career as a species, humans roamed over the landscape in small bands, subsisting as hunters, gatherers, and occasional scavengers. Being omnivorous, humans availed themselves of a variety of food sources opportunistically and eclectically, gathering edible plant products and killing some animals for their meat (as well as for their skin, bones, antlers, and other usable parts). In time, humans learned to manipulate their environment, initially through the creation of fires (Caldararo, 2002).

Although their lives were physically rigorous, they were venturesome and adaptable enough to spread out from their native African savannah into all the habitable continents. Relying on their ingenuity and tool-making ability, they adapted to widely varying environments – from icy northern Eurasia to arid Australia.

A dramatic change in human lifestyle began toward the end of the era known by geologists as the Pleistocene and the beginning of the current era, called the Holocene. That change evidently took place earliest in the Near East, some ten to twelve millennia ago, during what archaeologists call the Neolithic Age. As the last ice age ended, the warming trend gave rise to a profusion of plant and animal life in that region, which afforded humans an abundance of food sources and favorable sites for regular, and eventually permanent, habitation (Hillel, 1991).

As groups of humans shifted from nomadic to sedentary living and began to form settlements, they also learned, after collecting seeds of wheat and barley, to domesticate selected plants (Kislev *et al.*, 2004). Thus, agriculture began. At first it was in the form of rain-fed farming in relatively humid areas, and later it was in the additional form of irrigated farming in the main river valleys. Simultaneously, animal husbandry developed, based on the herding of livestock (sheep, goats, cattle, etc.) both in conjunction with village-based farming and in the context of an alternative lifestyle, namely semi-nomadic pastoralism.

Of the many plants with edible products, relatively few were found suitable for early domestication. Prominent among these were selected species of the *Graminea* family (the cereal grains of wheat, barley, oats, rye, and sorghum), the *Leguminosa* family (peas, lentils, chickpeas, and several types of beans), vegetables of various genera, and a number of fruit-bearing woody plants or trees (olives, grapes, almonds, pomegranates, figs, and dates). Similarly, only a limited number of animals lent themselves conveniently to domestication. Breeding programs, along with natural hybridization, played a pivotal role in shaping the genetic and evolutionary trajectories of domesticated animal species (Arnold, 2004).

Consequently, human societies abandoned their prior lifestyle as roaming hunter-gatherers, and, as they became sedentary producers of food, came to depend on their managed crops and livestock for subsistence. Agriculture has propagated plants and animals (e.g., wheat, rice, maize, cattle, swine, and poultry), which are some of the most prevalent and widespread organisms. Thanks to these organisms, humans have indeed become the dominant species on earth. An inextricable mutual dependency thus developed between humans and their domesticates.

The same processes of transition to an agricultural or pastoral economy, which first took place in the Near East, also appeared in at least seven independent centers (Smith, 1995) and rapidly spread from these places as

well. The latter centers included southern and eastern Asia, Central Africa, and Central America, each with its own indigenous selection of domesticable plants and animals. In all those locations, the agricultural transformation improved food security and thereby set in motion a progressive increase of population density. So productive has been the enterprise of agriculture that an ever-decreasing percentage of farm workers has been able to feed an ever-larger number of people. Urban centers then developed, in which people engaged in a variety of other occupations (industry, art, science, medicine, instituted religion, the military, and other societal functions), thus creating the basis for complex civilizations.

A less auspicious consequence of those same developments was a narrowing of the array of foods that served to sustain the population. The domesticated lifestyle provided only a limited number of tended species and strains, instead of the wide selection of types and sources of food that humans had previously been able to collect or hunt in the wild. As the variety of foods was reduced, so was the nutritional balance and quality of the diet. The study of archaeological remains from around the world reveals that the shift from hunting and gathering to increased nutritional focus on domesticated grains ($\sim$10,000 years ago) coincided with a decline in health, including increased evidence of morbidity related to dental abnormalities, iron-deficiency anemia, infection, and bone loss (Larsen, 2003). Moreover, reliance on a small number of crops and animals, maintained in managed sites, made societies vulnerable to failures of production resulting from the vagaries of weather as well as from pests and diseases of crops and livestock. People living in close communities, and eventually in cities, themselves became more vulnerable to communicable diseases.

So the great advantages of domestication were not without attendant disadvantages. However, with the increase of population density made possible by the initial success of agriculture, there could no longer be a return from permanent husbandry to the lifestyle and economy of nomadic hunting-gathering. Humans also changed biologically because of the selective pressures of living in built environments, decreased mobility, and changes in diet consistency associated with increasing sedentism (Leach, 2003). The agricultural transformation thus became effectively irreversible (Hillel, 1991).

As long as human exploitation of the land and its biotic resources was restricted to small enclaves, the surrounding expanses of relatively undisturbed natural ecosystems could remain intact, with their biodiversity preserved. But, as the extent and intensity of human exploitation of the terrestrial domain increased, along with the increase of population, natural habitats were reduced and fragmented. This process of human encroachment has continued and accelerated, until nearly half of the earth's continental

surface has come under direct human management. A similar process has occurred in the earth's aquatic (freshwater as well as oceanic) ecosystems (FAO, 2000). Even where humans have not intervened directly, the secondary effects of their activity (such as the chemical residues of industrial production) have caused indirect deleterious effects. Entire biomes are now threatened and numerous ''wild'' species have already been eliminated. Projections indicate that biodiversity loss will continue into the future, as expressed in declines in populations of wild species and reduction in area of wild habitats (Jenkins, 2003).

Within the agricultural lands themselves, poor management practices have induced processes of degradation. Denudation of the vegetative cover, coupled with surface pulverization by tillage or by the trampling of livestock or machinery, has made the soil vulnerable to erosion by wind during dry periods and by water during rainstorms. In extreme cases, the fertile topsoil has been completely scoured away, and the less fertile subsoil (or even the sterile bedrock) has been exposed. Soil productivity is thus greatly impaired, as is its capacity to support various forms of life (Hillel, 1991).

Quite another process of soil degradation occurs in irrigated lands, particularly in river valleys located in arid regions. There, the traditional practice of flood-irrigation with large volumes of water causes much percolation through the soil, which tends to raise the water-table, to saturate the soil excessively (a phenomenon called ''waterlogging'') and to accumulate salts at or near the soil surface (Hillel, 1998). The result is soil salination, a process that destroys soil productivity.

Fortunately, the picture is far from being entirely bleak. Many of the ills described can be prevented or alleviated. New trends and opportunities offer hope that further threats to biodiversity can be avoided. Human population growth seems to be slowing. Moreover, agriculture has already begun to develop and adopt better methods of production coupled with biological control and conservation, aimed at preserving, even enhancing, the diversity of life on earth (Edwards *et al*., 1993; Smith *et al*., 1995). The new approaches are impelled by a growing recognition of the indispensable importance of biodiversity to agriculture.

III. DEPENDENCE OF AGRICULTURE ON BIODIVERSITY

All the plants whose products are utilized by humans, either directly or indirectly (via plant-consuming animals), were derived originally from biological diversity; that is to say, from wild ancestors. So were all

domesticated animals. Those domesticates were selected and bred for their desirable traits, but as environmental circumstances and stresses change, as the requirements and preferences of humans change, and as domesticated organisms themselves are vulnerable to diseases and pests, the need arises repeatedly to breed new varieties.

Traditionally, agricultural breeding has been done with the close genetic relatives (either wild genotypes, or domesticated varieties or strains) of the relevant organisms. *In situ* genetic diversity is often considered a resource for future crop improvement (Ladizinsky, 1989). Different strains may contain different genes, including perhaps genes that impart resistance to certain pests and environmental stresses. Recently, new possibilities have arisen to transfer desired traits (genes) not just between strains of the same species, but even from one species to another, thus greatly enlarging the range of potential genetic resources available to agriculture (though the new techniques also present new hazards). Either way, breeding plants and animals for agricultural purposes was and remains dependent on nature's rich array of life forms, i.e., on natural biodiversity.

Of all the myriad species of plants or animals whose products can be useful to humans, agriculture utilizes directly only a few hundred. Among those, just 80 crop plants and 50 animal species provide most of the world's foods. However, what is not generally appreciated is that those relatively few species depend vitally for their productivity on hundreds of thousands of other species. Among the latter are insects and birds that pollinate crop flowers and feed on crop pests.

Even more numerous and varied are the microbial species that live on plants and animals, and are especially abundant in the soil. They too help to protect against pests, as well as serve to decompose residues (including pathogenic and toxic agents) and transmute them into nutrients for the continual regeneration of life, as well as to form and stabilize soil structure. Agricultural productivity and sustainability benefit from microorganisms in many ways, including the conversion by bacteria of elemental nitrogen from the atmosphere into soluble ammonium and nitrates that serve as essential nutrients for plants. Nitrogen-fixing bacteria may be either symbiotic (e.g., *Rhizobium* bacteria that attach themselves to the roots of legumes) or nonsymbiotic (free-living). Quite another function is fulfilled by mycorrhizal fungi, which live in association with crop roots and facilitate the uptake of phosphorus and other relatively immobile nutrients (Hartel, 2005).

Biological control agents (so-called because they prey on insects and other kinds of pests), as well as pollinators, generally reside in natural or seminatural ecosystems (Vandermeer, 1997). That is another reason for the importance of maintaining undisturbed areas in the vicinity of agricultural tracts. Clearing away such ecosystems in the belief that such action prevents the

invasion of pest species into fields and orchards may actually do more harm than good by depriving agriculture of beneficial organisms.

In ways both visible and invisible, agriculture thus depends on nature's biodiversity. Biodiversity operates not only on a present functional level, but also provides standing insurance against future extinctions, as well as evolutionary flexibility in regard to future climate change (Lande, 1988). Genetic diversity in wild populations is a substrate for both natural and directed selection. Hence, diminution of that diversity endangers agriculture just as it endangers all the processes of life on earth, which are inherently interdependent.

Growing conditions differ from place to place (due to differences in soil, water regime, temperature, exposure to sun and winds, day length, prevalence of diseases and pests, etc.), and also differ from season to season (due to the variability of climate). Therefore, pure stands of genetically similar, or essentially identical, plants are at greater risk than are genetically diverse stands. Conversely, genetically diverse crops can better survive in heterogeneous environments in which conditions fluctuate. Though the latter may not provide yields that are as great during favorable or normal seasons, they are more likely to provide an adequate yield during unfavorable seasons, during which pure stands (lacking genetic variety and hence adaptability to changing conditions) may be devastated by inclement weather or other disruptive factors.

A. Pollinators

Declines in pollination have been reported in every continent except Antarctica (Kearns *et al.*, 1998), and under-pollination for some crops caused by pollinator limitation already reaches 70% in some places (Reddi, 1987). This is significant because pollinators play a key role in agricultural productivity (Buchmann and Nabhan, 1996). While the majority of the world's staple crops (wheat, rice, maize, potatoes, yam, and cassava) are either wind- or self-pollinated, or are propagated vegetatively (Richards, 2001), many other important agricultural species do rely on pollinators. For instance, over 80% of the 264 species grown as crops in the European Union (EU) are dependent on insect pollination (Corbet *et al.*, 1991; Williams, 1996). In addition, the yield of tomatoes, sunflowers, olives, grapes, and soybeans—all major crops—is optimized by regular pollination (Richards, 2001). Fruit trees and legumes may be particularly hard hit by loss of pollinators, especially since they are grown intensively.

When compared to wind-pollinated plants, or plants that are pollinated by a wide taxonomic group, plants that have specialist animal pollination

(a 1:1 species relationship such as figs and fig wasps) have the lowest risk of pollen wastage during animal transport. They also have the lowest risk of pollen clogging and allelopathy because of heterospecific pollination. These same plants, though, have the highest risk of pollination failure if their pollinators are lost (Wilcock and Neiland, 2002). For this reason, decline in biodiversity may have cascading effects on species survivorship because it may disrupt these close-knit, highly efficient relationships. Just as a high diversity of pollinators may help increase the diversity of plants, a high diversity of plants supports more pollinators.

An experiment demonstrating the effect of habitat isolation (which often occurs in agricultural regions as native areas are converted to agriculture) on pollination has come from isolated "islands" of radish and mustard plants. The areas were set up in an agricultural landscape at varying distances from a species-rich grassland (Steffan-Dewenter and Tscharntke, 1999). Increasing isolation resulted in fewer bee visits per hour to the islands and also reductions in the taxonomic diversity of the visitors. Also, fruit and seed set declined with increasing isolation from the grasslands. In another study, the amount of woody border had a significant positive effect on the overall richness of insects at the family level in agricultural fields (Mänd *et al*., 2002).

B. Insect Pests

Small-scale farmers in the tropics have long used crop diversification as a way of minimizing the risk of crop failure. Vegetation or crop diversity has been frequently recommended as a way of reducing pest problems, and the lack of it has been blamed for infestations (Tonhasca and Byrne, 1994). Experimental studies and theoretical arguments suggest that the differences in pest abundance between diverse and simple systems can be accounted for by the response of herbivore host-finding behavior to patterns of resource availability (Risch *et al*., 1983).

The so-called "resource concentration hypothesis" (Root, 1973) applies to specialist herbivores and suggests that the presence of non-host species disrupts the ability of pests to attack their main host effectively. There have been several mechanisms enumerated that interfere with an insect's host-seeking behavior: camouflage—the host plant is guarded from insect pests by the presence of other plants; crop background—certain pests prefer certain backgrounds of a particular color and/or texture; masking or dilution of attraction stimuli—the presence of the non-host plant masks or dilutes the attractant stimuli of the host plant, leading to a breakdown or re-orientation of feeding and reproduction; and repellent chemical stimuli—aromatic odors of certain plants disrupt the insect's host-finding ability.

Some mechanisms interfere with pest populations as a whole. These include mechanical barriers, such as companion crops that block the dispersal of herbivores across the polyculture; lack of stimuli that causes the herbivore landing on a non-host to leave the plot quickly; and microclimate influences. As shown in the rice-blast study (see Box), favorable aspects of microclimate conditions may become highly fractionated, causing the insects to experience difficulty in locating and remaining in suitable microhabitats (Zhu *et al*., 2000).

Other field studies have supported the hypothesis that increasing crop diversity will decrease pest abundance. For instance, lepidopterous stem-borers constitute one of the major constraints to efficient maize and sorghum production in the developing world (Ampofo, 1986). Ogol *et al.* (1999) investigated the effect of using an agroforestry system involving maize and the tree legume *Leucaena leucocephala* in western Kenya. Abundance of adult and larval/pupal stages of maize stem-borers, oviposition preference, foliar damage, borer entry/exit holes, maize plant mortality and stem breakage because of borer damage were significantly greater in the maize monocrop than in the maize-leucaena intercrop. The reduced pests in the maize-leucaena plots were associated with reduced yield loss per plant, and the 3.0 m leucaena hedgerow spacing plots yielded more than the maize monocropped plants even though they had 25% fewer maize plants to begin with.

During a good part of the twentieth century, farmers throughout the world relied heavily on chemical pesticides (Pimentel, 1997). But often these pesticides kill natural enemies and provoke resistance in the pest they are intended to kill. The absence of natural enemies may allow benign insects to increase their population to such an extent that not only do they become pests, they are also able to acquire resistance to pesticides. This pattern is known as the 'pesticide treadmill' (Vandermeer, 1997). In Central America, for instance, a host of predatory and parasitic arthropods was removed from the agriculture system, and its loss resulted in greater problems, to the point that the cotton industries of Guatemala, El Salvador, and Nicaragua were severely damaged.

In the last decades of the twentieth century, an increasing awareness of the limitations and damages associated with chemical pesticides has led to the development of sophisticated techniques of "integrated pest management" (IPM). Such methods are based on the judicious combination of biological controls, together with sparing applications of chemicals only when absolutely necessary. The biological control component of IPM, in turn, depends on ecosystem biodiversity. For example, spiders are one of the species that show great potential as biological control agents (Nyffeler and Sunderland, 2003).

GENETIC DIVERSITY AND DISEASE CONTROL IN RICE

Zhu *et al.* (2000) studied genetically diversified rice crops that were planted in fields in Yunnan Province, China, to test the effect of such a planting on rice blast disease. *Magnaphorthe grisea*, the fungus that causes blast disease, interacts on a gene-for-gene basis (Baker *et al.*, 1997; Staskawicz *et al.*, 1995) with its host and has a very varied pathogenesis (Ou, 1980). It exists as a mixture of genetic variants that attack host genotypes with different resistant genes. For this reason, host-resistance genes often remain effective for only a few years in agricultural production before succumbing to new pathogenic races (Ou, 1980). Yunnan Province has a cool, wet climate that fosters the development of the blast. To control it, farmers make multiple foliar fungicide applications.

When mixtures of rice varieties were planted, blast was controlled so well that only one foliar fungicide spray was applied. When these mixtures were compared to monocultures, the researchers found that the diversification had a substantial impact on rice-blast severity. Panicle-blast severity on the valuable glutinous varieties averaged 20% in monocultures, but was reduced to 1% when dispersed within the mixed population. Blast severity also decreased, to a smaller extent, among the hybrid varieties.

Canopy microclimate data collected at one survey site in 1999 indicated that height differences between the taller glutinous and shorter hybrid varieties resulted in temperature, humidity, and light conditions that were less conducive for glutinous blast than those in the uniform crop heights of the monocultures. Induced resistance (which occurs when inoculation with a virulent pathogen race induces a plant defense response effective against pathogen races that would normally be virulent on that host genotype) may have also played a role in reducing the blast occurrence in the mixed rice fields (Zhu *et al.*, 2000).

C. Disease Control

Genetic diversity is likely to reduce the odds of crop failure and to contribute to greater stability of production. Similar benefits may be inherent in mixed-species and multi-species cropping systems, such as are common in subsistence farm units. In contrast, uniform monoculture crops, standing like battalions of identical soldiers in close formation, may produce high yields in favorable conditions but fail badly under the influence of suboptimal or anomalous conditions. Pathogens spread more readily, and epidemics tend to be more severe, when the host plants (or animals) are more uniform, numerous, and crowded. Owing to their high densities and the large areas over which they are grown, both crop plants and livestock are repeatedly

threatened by ever-new infestations of pests and diseases. Existing pests and diseases are continually evolving strains that overcome the innate defenses of particular strains or breeds, as well as of chemical treatments applied by farmers.

Many historical examples can be cited to prove that monoculture stands or concentrations of crops and livestock with uniform genetic traits, though they may be more productive in the short run, entail the risk of succumbing, sooner or later, to changing conditions. Catastrophic outbreaks of disease, invasions of insects, and climatic anomalies have caused many wholesale crop and animal destructions in the past. Such episodes have resulted in famine, especially where, in the absence of sufficient diversity, no varieties or breeds were present that could withstand the destructive outbreaks.

Among the notable examples of disastrous outbreaks are the infestation of red rust on wheat in Roman times, the mass poisoning from ergot-tainted rye during the Middle Ages in Europe, the failure of the vaunted vineyards of France in the late nineteenth century, and the potato famine that hit Ireland in the 1840s and 1850s. The latter was caused by the fungus *Phytophthora infestans*, which arrived accidentally from North America and attacked the genetically uniform potato stock that served as the mainstay of Irish farms. As a result, about 1.1 million people died from starvation or typhus and famine-related diseases, and 1.5 million people immigrated to North America in just the famine years (Mokyr, 2004).

There is reason to be concerned, especially over the massive concentration of agricultural production (and of food consumption) on three primary crops—wheat, rice, and maize—which together account for over half of the total nutritional energy derived from crop plants in the world at large. In principle, such a concentration creates vulnerability. One example of the vulnerability of wheat is the recent outbreak of scab—*Fusarium* head blight—on wheat and barley in Minnesota and the Dakotas. Many farmers in areas where scab has been severe are forced to abandon farming for lack of alternative crops to grow profitably (McMullen *et al.*, 1997). Ultimately, the best insurance against the future failures is the enhancement of biodiversity, both to allow improvement of those crops and to discover appropriate substitutes for them.

D. Birds

Donald *et al.* (2000) investigated the relationship between agricultural intensification and the collapse of Europe's farmland bird population, and found that population declines and range contractions were significantly greater in countries with more intensive agriculture. The effects are

discernible at a continental level, making them comparable in scale to deforestation and global climate change as major anthropogenic threats to biodiversity.

Sinclair *et al.* (2002) studied the effects of agriculture on avifauna in the Serengeti by comparing agricultural fields with native savannah and grasslands. The authors documented a substantial but previously unnoted decline in avian biodiversity in the agricultural lands. The abundance of species found in agriculture was only 28% of that for the same species in native savannah. Insectivorous species feeding in the grass layer or in the tress were the most reduced. Some 50% of both insectivorous and granivorous species were not recorded in the agricultural sites, with ground-feeding and tree species the most affected. Although there was a concurrent decline in insects in the agricultural regions, the authors noted that the great reduction in insectivorous birds would be likely to affect their ability to control insect-pest outbreaks. Also, the lack of raptors in the agricultural sites, particularly those that consume rodents (e.g., black-shouldered kite [*Elanus caeruleus*] and long-crested hawk eagle [*Spizaetus ayrestii*]) and that are abundant in the savannah, may contribute to the frequent outbreaks of rodents such as the Natal multimammate mouse (*Mastomys natalensis*) in the agricultural zones.

E. Cultivated Plants and Wild Relatives

Though clear benefits do exist in planting agricultural lands near wild ones, the action is not without potential consequences. One often-problematic process that has gained attention occurs when cultivated crops breed with their wild relatives (Ellstrand, 2003; Ellstrand and Schierenbeck, 2000). Although France's sugar-beet seed production fields are many kilometers from the wild sea beets growing along the Golfe du Lion, the sea beets have been able to pollinate the sugar beets being grown for seed production. As a result, by the mid-1970s, northwestern Europe's sugar-beet fields had become pocked with beets that were flowering prematurely, or "bolting," a trait of the wild relatives. Investigation found that these bolters were the result of cultivated beets being pollinated by their wild beet relatives.

The problem is not unidirectional. Just as wild alleles can move into domesticated crops, alleles from domesticated crops can move into wild populations. Individual crop plants typically contain less genetic variation than individual populations of their wild relatives (Ladizinsky, 1985, 1989). The evolutionary result of continued substantial gene flow from a single cultivar to a wild population would be a decrease in genetic diversity. It is also possible that some wild species might become extinct because of assimilation with the crop species. Also, the hybridized wild species may suffer from sterility, and thereby wild populations may be reduced.

A literature review (Ellstrand and Schierenbeck, 2000) found 28 well-documented examples in which interspecific hybridization preceded the evolution of new lineages that became either weeds in managed ecosystems or invasives in unmanaged ones. Ellstrand also found that spontaneous hybridization between a given crop and at least one wild relative somewhere in the world is the rule rather than the exception (Ellstrand, 2003). For the 25 most important food crops, all but three have some evidence for hybridization with one or more wild relative, causing a wide array of effects.

For instance, natural hybridization with cultivated rice has caused the near-extinction of the endemic Taiwanese taxon *O. rufipogon spp. formosana* (Oka, 1992). Collections of this wild rice over the last century show a shift toward characteristics of the cultivated species and a decline in fertility. Throughout Asia, typical specimens of other subspecies of *O. rufipogon* and the wild *O. nivara* are rarely found because of extensive hybridization with the crop (Chang, 1995). Also, hybridization with maize may have played a role in the extinction of the populations that were maize's progenitors (Small, 1984).

While growing crops near natural areas has many advantages, the dangers of gene flow need to be considered. Surrounding a field with plants that would interfere with pollen transfer can help reduce gene flow. Such plantings are often used to enhance the effect of isolation distance. Saeglitz *et al.* (2000) found that planting hemp around a sugar-beet crop was effective in preventing contamination from plants outside the crop space. Similarly, "trap crops" or forest borders for field crops might not only be beneficial in preventing gene flow, they might also offer other benefits of biodiversity such as pest management.

IV. GENETIC BASES OF AGRICULTURAL CROPS

Genetic diversity within each species of crop—that is, among its wild progenitors or relatives, as well as among its cultivated varieties and strains—has long been a foundation of agriculture. Traditional methods of plant breeding, based on the selection and cross-breeding or hybridization of genetically distinct strains, are still the most commonly used. They have been and continue to be used in the effort to improve crop immunity or resistance toward such yield-reducing factors as fungal diseases or insect infestations, as well as to improve crop adaptation to environmental stresses such as heat spells, dry spells, or salinity.

The preservation of genetic diversity among wild plants can best be achieved in the natural setting, within native habitats and living ecosystems. The preservation of agricultural cultivars can be accomplished in designated fields and greenhouses. Both of these are termed "*in situ* preservation."

Where such methods of living-plant preservation are not practical or sufficient, further efforts must be made to preserve the seed stocks of numerous species and varieties *ex situ*, in specially organized and carefully maintained collections. Such collections can serve as genetic pools, from which plant breeders may draw genes that can impart to new varieties superior tolerance or resistance to pests, diseases, or weather anomalies. The need for improved varieties arises repeatedly, as new pests appear or as old pests themselves acquire immunity to prior modes of control.

Large seed-storage facilities (called seed banks) have been organized and are maintained by such agencies as the U.S. Department of Agriculture, the various units of the Consultative Group on International Agricultural Research, and many other national and international organizations. (The Food and Agriculture Organization of the United Nations maintains a global listing of crop varieties.) The seed banks hold large collections of "landraces" (farmers' indigenous cultivars) and wild relatives of crop species, as well as modern crop varieties and special breeding stock. They are intended to be preserved indefinitely as sources of genetic diversity for future breeding work. Great progress has been achieved in organizing and maintaining such facilities, yet much more can and should be done to enlarge, improve, and coordinate the various seed banks throughout the world.

V. BIODIVERSITY IN THE SOIL

Soils are among the most species-rich habitats on the planet (Brussaard *et al*., 1997; Wall, 2004; Wall and Virginia, 2000). Almost every phylum known aboveground is represented in soil, and each with a wealth of species diversity. Yet, it is estimated that few of these species, perhaps fewer than 10%, have been identified and described (Groombridge, 1992).

Life in soils includes vertebrates (e.g., prairie dogs, gophers, lizards, pack rats), macrofauna (large invertebrates up to several centimeters long, e.g., ants, termites, millipedes, spiders, centipedes, earthworms, enchytraeids, isopods, snails), micro- and meso-fauna (microscopic invertebrates less than a millimeter in length) such as the tardigrades, rotifers, nematodes, and mites), as well as algae, lichens, protozoa, fungi, bacteria, and viruses (Wall Freckman *et al*., 1997). The abundance of these organisms is astounding. A cubic meter of a grassland soil can harbor millions of organisms—10 million nematodes, 45,000 oligochaetes, 48,000 mites and Collembola, and thousands of millions of microorganisms (Overgaard-Nielsen, 1955).

Numerous species in soil are directly involved in ecosystem processes and ecological services that contribute to sustaining agriculture (UNEP,

2001; Daily *et al*., 1997; Pankhurst and Lynch, 1994; Wall, 2005; Wall and Freckman *et al*., 1997). These include maintenance of soil fertility through the decomposition of organic matter and the cycling of nitrogen and carbon; maintenance of soil structure and hydrological cycles through aggregation of soil particles and increased soil aeration; burrowing and transfer of soil organic matter and other microscopic biota throughout the soil; influencing plant community diversity and plant fitness through symbiotic, mutualistic and parasitic associations (Bardgett *et al*., 2001; Hendrix *et al*., 1990); influencing soil carbon sequestration and trace gas flux; and contributing to air and water purification by degrading pollutants (Coleman and Crossley, 1996). Through these many connections, soil biota are an essential and intimate link to ecosystem functioning in aboveground terrestrial systems, and to freshwater and marine sediments (Wagener *et al*., 1998; Wall Freckman *et al*., 1997).

Soil biodiversity is determined by multiple factors: vegetation (chemical quality, quantity or biomass, plant species, community composition), soil physical and chemical properties, climate, and the interactions among soil organisms (Anderson, 1995; Giller *et al*., 1997). In natural systems, these factors have been integrated over time, resulting in associations between soils, aboveground biota, and climate (Hooper *et al*., 2000). Disturbances affecting soils can impact ecosystem functioning and ecosystem services, and can test our ability to manage soils sustainably.

Land-use change is the major global-change driver affecting soils. Conversion of natural systems to agriculture diminishes the diversity of plant species as well as of microbes (Wardle *et al*., 1999), mycorrhizae (Thompson, 1987), nematodes (Freckman and Ettema, 1993; Wasilewska, 1997), termites (Eggleton *et al*., 1997), beetles (Nestel *et al*., 1993) and ants (Perfecto and Snelling, 1995). Land-use change that increases soil compaction and texture affects the diversity and abundance of vertebrates and larger invertebrates because their habitat is often dependent on specific soil conditions (Anderson, 1987).

There is considerable evidence indicating that disturbance to the soil habitat in natural ecosystems affects soil biodiversity (Freckman and Ettema, 1993; Wardle and Lavelle, 1997; Wardle *et al*., 1998), with cascading effects on other soil properties such as decreases in water infiltrability, carbon and nutrient content, oxygenation, salinity, and erosion (Pimentel and Kounang, 1998; Wolters *et al*., 2000). Land-use change, atmospheric deposition (e.g., acid rain, nitrogen), pollution (sewage, excess fertilizer, toxic chemicals), and invasive species (plants, animals) can alter the plant species, distributional pattern, chemical quality of the plant, root abundance and architecture, soil microclimate, and the resulting food base for the soil community. For example, a sudden change in plant composition that results in non-host plants has immediate effects on the decline in diversity

of primary consumers, root pathogens (e.g., obligate parasites—fungi, bacteria, plant-parasitic nematodes), and symbionts (mycorrhiza, rhizobia) (Sasser, 1972; Rovira, 1994). These changes to plants can, over time, affect plant fitness and community composition.

In general, it is easier to sustain soils and prevent degradation than to try to restore the soil community and functioning of degraded soils. Efforts at soil reclamation across large scales, whether from disturbances due to intensive chemical use in conventional agriculture, agricultural forestry, fire, or pollution, have focused generally on supplying a sufficient amount of organic matter in the form of plants or plant litter as a substrate base for "reclaiming" the soil community. In all cases, the objective is not necessarily to recreate the original soil species diversity of the pre-affected natural soil but to restore the functioning of the soil community; for example, to enhance vegetation growth, decrease toxicity of chemicals, and promote soil structure.

In agricultural soils, the set of practices included in the term "conservation tillage" incorporates plant organic matter residues in soils. Over time, the enhanced soil food web mimics the functions of natural systems (Hendrix

EUTROPHICATION

Inappropriate agronomic management may affect biodiversity in freshwater aquatic systems associated with agricultural lands. Eutrophication of lakes, ponds, rivers, and estuaries, due to excessive nutrient deposition derived from soil erosion, fertilizer residues, and animal manure, can have adverse affects on aquatic ecosystems by deprivation of oxygen and by promotion of toxin-producing algal blooms. These blooms alter marine habitats through shading and overgrowth and adversely affect fish and other marine organisms. Animals, including humans, who consume fish and shellfish contaminated by Harmful Algal Bloom toxins may develop paralytic, neurotoxic, or amnesic shellfish poisoning. In the southeastern United States, the emergence of the dinoflagellate *Pfiesteria piscicida* in the 1990s has resulted in the death of tens of thousands of fish in estuarine waters and rivers. Human health effects were also reported. Discharges of swine and poultry waste into rivers have been implicated in creating the conditions for such toxic algal blooms in coastal areas. Aquaculture activities may also play a role in the outbreaks. In the past, only a few regions of the U.S. were affected by harmful algal blooms. Now, virtually every U.S. coastal state has reported serious blooms, which may be responsible for more than $1 billion in losses in the last two decades through direct impacts on coastal resources and communities (NOAA, 2004).

et al., 1986; Freckman and Ettema, 1993). Earthworms present with no-till systems, for example, generally improve water infiltration and provide channels that facilitate root penetration (Edwards and Lofty, 1980), although increased nutrient leaching can occur. Soil moisture is enhanced, soil carbon is sequestered, and soil quality and structure are improved (Rovira, 1994) in comparison to soils that are intensively managed through tillage.

VI. GENETIC MODIFICATION OF FOOD SPECIES

Modern biotechnology, including the generation of genetically modified species of crops, has increased awareness of the value of biodiversity, both within and among species. The prospect of transferring useful genes to completely unrelated plants greatly enlarges the pool of genes potentially available to crop breeders (Garcia-Olmedo, 1998). As examples, we may cite the transfer of a gene conferring protection toward insects from bacteria to maize, cotton, and potatoes. This should serve as a further inducement to preserve the full panoply of biodiversity, for utilitarian reasons (the anticipated benefit to human society), in addition to the fundamental ecological and ethical reasons for doing so.

A. Opportunities and Risks

Among the successes cited for biotechnology are the insertion of Bt genes (from strains of the insect pathogen *Bacillum thuringiensis*) into maize, potato, and cotton to impart to these crops an inherent resistance to certain insect pests. Rice has also been modified. In one case, beta-carotene was produced and in another an undesirable component for sake brewing (glutelin) was reduced (FAO/WHO, 2000).

However, the development of biotechnology and genetic engineering is not problem-free. Behind the hoped-for benefits lurk potential pitfalls. Like all plant-breeding techniques, there can be unexpected effects. The decrease in glutelin levels in rice, for instance, was associated with an unintended increase in levels of prolamines, which could affect nutritional quality and allergenic potential (FAO/WHO, 2000). Modified organisms may escape from greenhouses and fields into natural, or quasi-natural, ecosystems, and disrupt their biodiversity. (Such an invasion of ''alien'' species of fish has already been noticed in the context of mariculture). Also possible, as discussed above, is that pollen from transgenic crops can fertilize wild relatives, and thereby transfer the transgenes outside human control.

Another insidious possibility is that large commercial corporations, under the patent laws and the protection of "intellectual property rights," will appropriate the benefits to themselves. Many consider it unfair that the culminated work of generations of scientists, researching and publishing openly and cooperatively, should now be sanctified as the commercial property of exclusive groups, theirs to grant or withhold according to their profit interests. The concentration of vital scientific knowledge and its exclusive application to the benefit of a few enterprises should be prevented (Thompson, 1998).

Apart from the general ethical question this arrangement raises, there is the specific conflict of interests between the large, multinational corporations and the people of the developing nations who are most in need of assistance. It is generally the developing nations from whose territory the useful genetic material had been extracted in the first place. Now these nations may well find themselves unable to pay for the same genetic material after it has been put into directly useful form (i.e., incorporated into products or into new varieties of crops), and commercialized. Investments should be made at the source to stimulate the national capacity of developing countries to realize the potentialities of their own varieties and seed systems (FAO, 2004).

The application of genetic transformation techniques to crop plants raises an important question relevant to the current trend toward loss of biodiversity: Does this technology offer the potential for mitigating the problem; or – contrariwise – does it pose a danger of exacerbating it? Proponents of the new technology contend that it can help to intensify production in favorable lands, thus alleviating the pressure on, and preventing the further degradation of, agriculturally marginal lands and their natural ecosystems. Opponents of the same technology fear that it can damage biodiversity in various ways, such as by permitting the greater use of pesticides and by introducing exotic genes and organisms that may disrupt natural plant communities. Other objections pertain to the exclusive commercial appropriation and exploitation of the technology, which may indeed hinder the free exchange of information and ideas that has always been the hallmark of science, to the special detriment of the poorer countries. Hence the entire issue must be approached with discernment and caution.

Even prior to the birth of transgenic technology, the traditional plant-breeding methods that had evolved over the past ten millennia have allowed extensive genetic alterations of the genomes of crop plants. Plant genomes, having about 25,000 genes each, have undergone numerous changes in the course of the improvement of their (both multigenic and oligogenic) agronomic traits (Garcia-Olmedo, 1998). Classical breeding techniques are still the most effective approach to dealing with traits that are dependent on multiple genes distributed over the entire genome. On the other hand, genetic engineering appears to be preferable in manipulating traits that depend on one or a few genes.

In the process of acquiring their agronomic traits, crop species ceased to be ‘‘natural’’ in that they lost the ability to survive by themselves in the open environment. Indeed the genetic alterations achieved through domestication have been profound. The recombinant DNA technology, however, is opening possibilities that were out of reach by the traditional methods of breeding. Prominent among these possibilities are the productions of various biodegradable polymeric compounds (plastics), oils of industrial uses, as well as pharmaceuticals.

The attainment of higher yields and the development of more environmentally sustainable practices have been and will continue to be the main challenges of agriculture. In 2025, the world's ~8 billion people will require an average world cereal yield of about 4 metric tons/ha. There will also have to be an approximate doubling of global use of synthetic nitrogen to produce the 3 billion tons of grain needed (Dyson, 1999). Owing to demographic growth, available agricultural land per capita has steadily diminished in recent decades from about 0.5 hectare to half that figure, and in the next twenty years it is projected to be further reduced to perhaps 0.15 hectare. On a global scale, therefore, there is no option but to increase the per-hectare yields of all the main crops. The intensification of production on the most favorable lands should obviate the necessity to expand farming by further invading, and destroying, the remaining natural habitats (many of which are marginal for farming in any case).

Traditional plant-breeding objectives have included the enhancement of traits that are directly related to increased yields, as well as the improvement of quality and other traits that are considered economically desirable. Most of the transgenic crop plants that have been approved for cultivation so far also address the same objectives of higher yields in the context of a cleaner agriculture. In effect, pest- and disease-resistant cultivars have the potential to increase yields by reducing losses (such as those due to pests) while reducing the need for various agro-chemicals. For example, herbicide-resistant cultivars permit minimum tillage, a practice that in turn serves to protect the soil against erosion and to maintain the biota and fertility of the topsoil. However, the consequent increase in the use of herbicides may also disrupt biodiversity, both within and outside the target cropland. The question of whether or not the advantages outweigh the potential disadvantages requires careful case-by-case examination.

The effects of genetically modified herbicide-tolerant (GMHT) and conventional crop management on invertebrates (herbivores, detritovores, pollinators, predators and parasitoids) have been compared in beet, maize, and spring oilseed rape sites throughout the United Kingdom. In general, the biomass of weeds was reduced under GMHT management in beet and spring oilseed rape and increased in maize compared with conventional treatments (Hawes *et al.*, 2003). In maize, the weeds probably increased

because of the higher persistence and greater efficacy of herbicides used in the conventional treatment. Herbivores, pollinators, and natural enemies changed in abundance in the same directions as their resources, and detritivores increased in abundance under GMHT management across all crops. The experiment suggests that the impact of GMHT cropping on invertebrate biodiversity acts primarily through changes in weed flora (Hawes *et al.*, 2003).

In another study of the same crops, numbers of butterflies in beet and spring oilseed rape and of Heteroptera and bees in beet were small under the relevant GMHT crop management, whereas the abundance of Collembola—soil and litter dwellers—was consistently greater in all GMHT crops (Haughton *et al.*, 2003). It is worth noting that experimental evidence from several countries also suggests that invertebrate populations could be affected in GMHT crops through the reduced biomass and diversity of weeds. The most consistent effects appeared through the timing of the application of herbicides. Experiments with GMHT sugar and fodder beet in Europe showed that leaving weeds to be controlled later favored a range of invertebrates, including natural enemies of crop pests (Squire *et al.*, 2003).

Some applications may not respond to the main challenges while addressing specific sectoral demands, from alterations of post-harvest properties for food processing (such as delayed-ripening tomatoes) to those that meet certain nutritional requirements (such as the enhancement of provitamin A and iron in rice). The relevance of such applications must be weighted in relation to their specific merits or shortcomings in each case.

Transgenic technology has found an increasing number of applications, notwithstanding the objections and warnings of its critics. Its proponents claim that it has the potential to reconcile the needs of a growing population with the goal of conserving and promoting biodiversity. Over 40 million hectares of transgenic crops are already grown in over a dozen countries. New techniques allow the development of transgenic plants whose purpose is to serve in the screening of new generations of agrochemicals that are intended to meet the requirements of higher specific activity (hence decreased application amounts per hectare), greater selectivity (so that they may affect only the target organism to be controlled), and higher biodegradability (so that they may not accumulate and persist in the environment).

Plant biotechnology also holds promise in the creation of medical products such as vaccines. In Africa, for instance, tobacco plants are being used to develop an affordable vaccine against the virus that causes cervical cancer. The reason for making vaccines in plants is that it may cut costs by orders of magnitude because it obviates the need for a fermentation plant, for yeast or bacteria, as well as a tissue-culture facility for human or animal tissue culture (Mthembu, 2004). The use of transgenic plants to produce vaccines could

allow easier access, cheaper production, and an alternative way to generate income (Royal Society of London *et al.*, 2000).

B. Addressing Biosafety Issues

The safety of biotechnology is a complex issue for which there is no simple answer, as it depends on the specific nature of the induced change and its actual performance in the environmental context (Garcia-Olmedo, 1998; Hillel *et al.*, 2002). This issue must therefore be treated on a case-by-case or application-by-application basis. In principle, however, no human endeavor is entirely devoid of risk, and that risk increases whenever humans act without knowing or fully understanding the potential consequences.

As in the approval of any technological innovation, the application of each proposal for transgenic application must be evaluated on the basis of benefits versus risks. Those risks must be monitored closely and continuously, retaining the possibility that the approval may be rescinded if the expectation derived from initial assessment is not borne out.

The concept of substantial equivalence, which implies a direct comparison of the proposed innovation with what is currently in use, may offer a rational approach to the problem (FAO/WHO, 2000). Both intended and unintended effect must be monitored and assessed. Intended effects can be generally evaluated by well-established standard protocols, which are not restricted to transgenic products. In addition, new tools—high throughput genomic proteomic and metabolic methods—have been developed that allow the investigation of unintended effects (Garcia-Olmedo, 1998). Those effects of genetic alteration, predictable or unpredictable, must be evaluated by methods independent of those used to achieve the respective alterations (whether by classical breeding or by genetic engineering).

Safety considerations concerning possible effects of transgenic products on human subjects should address possible toxic effects and potential allergenic effects. Standard toxicity tests can be performed with transgenic material, using the isogenic non-transgenic material as control. Additionally, toxicity of new products differentially present in the transgenic line, whether intended or unintended, can be individually assessed as required.

Allergy problems evidently affect an increasing number of urban dwellers, for reasons that are not entirely known (FAO/WHO, 2000). A considerable number of items present in daily life—from rubber to peanuts—can cause allergic reactions in sensitive individuals. Molecules (allergens) or their parts (epitopes) that cause such reactions have been identified. Under current legal framework, no gene encoding a known allergen may be expressed transgenically for commercial use and no gene from a particularly allergenic species

may be transferred unless there is positive evidence that the gene product is not responsible for the observed allergy.

Once a gene has been transferred to a particular species, it becomes an integral part of the genetic makeup of the recipient species and will have the same fate as the remaining thousands of genes that constitute the genome. Interspecific genetic fluxes occur in nature to a very limited extent and are subject to barriers that are breached only rarely. A pollen grain must fly a certain distance, find an appropriate and mature recipient, pollinate, yield a viable seed capable of developing into a non-sterile mature plant and, finally, the progeny of this plant must be viable. For certain transformation events, accidental gene transfer to other species is highly unlikely, whereas for others there is a certain non-negligible probability of occurrence. These cases should be subjected to experimental evaluation.

There is generally no danger of plant gene transfers into the genomes of humans or other animals. Humans and other animal species have daily consumed thousands of different such genes, yet no evidence has been found in animal genomes of this type of horizontal transfer. The use of antibiotic resistance as a marker for selection in GM plants for human use, though, has also resulted in a fear that these genes may be transferred to those bacteria that cause disease in humans. There should be further research into alternatives to antibiotic-resistance marker genes, as having antibiotic-resistance genes present in new GM crops under development for potential foods is no longer acceptable (Royal Society of London, 1998).

The transfer of genes from cultivated species to related wild species in the same habitat occurs with a probability that is different for each species-habitat combination (Royal Society of London, 1998). Whether the species is autogamous or allogamous, and whether or not there are closely related wild species in the vicinity of the cultivated one, determine the relevance of this issue in the approval procedure. Several million hectares of transgenic canola are currently cultivated in the North American continent, after initial approval, and the entire operation is under close monitoring. The results of these observations will be important to the future of this transgenic crop.

Gene transfers to nontransgenic cultivars of the same species only require appropriate synchrony and are limited by distance. This type of transfer is believed by proponents of the genetic-modification technology to be neither a health risk nor an environmental risk. Nonetheless, it is a commercial requirement that it be countered by planting a number of rows of non-transgenic material around each transgenic field, by keeping regulation distances between transgenic and non-transgenic plots, and by monitoring adventitious events by using highly sensitive analytical methods (Royal Society of London, 1998).

The environmental safety of transgenic crops involves two additional aspects that require special attention. These are the possible effects on non-target organisms and the possible induction of resistance in the target organisms.

When genetic resistance to a particular target organism (bacteria, fungi, insects, and others) is introduced into a given cultivar, possible short-term and long-term effects on non-target organisms must be evaluated. This evaluation should consider current practice as control. Thus, for example, the effect of the introduction of Bt cotton on beneficial insects should be compared with the effect of the repeated insecticidal treatments that accompany the cultivation of non-transgenic cultivars. Transformation events that have been approved so far for plant protection are claimed to be more environmentally friendly than current technologies (which generally involve the use of pesticides) (Garcia-Olmedo, 1998).

Induction of resistance in any target organism is to be expected sooner or later, whether it involves insecticides, antibiotics, or other agents. This induction can be either accelerated by malpractice or retarded by judicious management. In the case of transgenic plants that are resistant to insects, microbial diseases, or weeds, the implementation of proper management techniques (such as the provision of refuges, adequate doses, etc.) should be in the interest of all parties involved (farmers, authorities, and commercial enterprises).

THE MONARCH BUTTERFLY AND BT MAIZE

Concerns regarding the nontarget effects of transgenic crops containing transgenes from the organism *Bacillus thuringiensis* (*Bt*) arose after the publication by Losey *et al.* (1999) on the potential risk of maize pollen expressing the lepidopteron-active Cry protein to the monarch butterfly, *Danaus plexippus* L. A collaborative research effort by scientists in several states and in Canada, though, found after two years of study that the impact of Bt maize pollen from commercial hybrids on monarch butterflies was negligible (Sears *et al.*, 2001). The only transgenic maize that consistently affected monarchs was from a hybrid that is currently $<2\%$ of the corn planted in the U.S. and for which re-registration has not been applied (Hellmich *et al.*, 2001). However, the Bt-supportive studies assume that monarchs only consume pollen, and not other maize tissues. Obrycki *et al.* (2001) pointed out that the presence of anthers on milkweeds is of considerable importance because of the higher concentrations of Bt toxins that they contain. Besides their earlier research (Losey *et al.*, 1999), which showed that pollen/anther mixtures were deleterious to monarch larvae, 2001 field observations and experimental evidence suggest that monarchs may be exposed to more maize anther material than previously assumed.

VII. CLIMATE CHANGE AND AGRICULTURAL BIODIVERSITY

The climatic consequences of increasing greenhouse gases are likely to include far-reaching changes in agriculture, as well as in natural ecosystems (Rosenzweig and Hillel, 1998; IPCC, 2001). Climate change will affect the regional patterns of temperature, precipitation, and evaporation, indeed the entire array of meteorological, hydrological, ecological, and agricultural relationships. Agricultural biodiversity will be affected by the magnitude and rate of climate change, and by its geographical and seasonal patterns. The functioning and productivity of agro-ecosystems in different countries and regions will be altered. Some regions may benefit, while others suffer. Thus, threats to agricultural biodiversity are among the most serious of potential damages resulting from a change of climate.

The projected climate effects associated with increases in anthropogenic greenhouse gas emissions (including warmer temperatures, changed hydrological regimes, and altered frequencies and intensities of extreme climatic events) may inhibit crop production in some regions. Differential plant responses to higher concentrations of atmospheric CO_2 (Kimball *et al.*, 2002) may also contribute to changes in biodiversity. Agricultural pests, overall, are likely to thrive under conditions of increasing atmospheric CO_2 concentrations and rapid climate change. A host of interactive changes in crop growth flow from these primary effects, some resulting in positive feedbacks and others in negative ones. All these changes, in concert, could have major impacts on the prospects for long-term food security.

A. Shifts in Agro-Ecological Zones

As new areas become suitable for crop production while old agricultural areas become less so, the geographic shift of agriculture may encroach on natural ecosystems. This is more likely to occur in high-latitude and high-altitude regions as warming temperatures prolong growing periods. It may also occur in lower latitudes due to changes in hydrological regimes. Biodiversity in the affected ecosystems may be compromised.

Even apart from agriculture, climate change is likely to modify the zonation and bioproductivity of forests, grasslands, savannahs, wetlands, tundras, and other biomes. A warmer regime might disrupt the prior adaptation of native plants and animals to their existing habitats. The flooding and waterlogging of some areas and the aridification of others could weaken currently vigorous biotic communities. For example, the thawing of

permafrost could dry out tundras, just as the invasion of seawater can destroy freshwater wetlands (estuaries, deltas, marshes, lagoons) near coastlines.

The rate of climate change may be too rapid to allow some natural communities to adjust, and where evolving climate becomes increasingly unfavorable there could be a large-scale die-back of forests. Associated species that depend on these forest ecosystems may then be threatened with extinction. In this manner, climate change constitutes a threat to biodiversity in general, and to the survival of vulnerable or endangered species in particular. Conversely, some types of forests and other biomes may expand and become more vigorous as a consequence of the warming trend and enhanced photosynthesis, demonstrating beneficial effects as well.

B. Pests and Climate Change

Climate affects not just agricultural crops but their associated pests as well. The major pests of crops include weeds, insects, and pathogens. The distribution and proliferation of weeds, fungi, and insects is determined to a large extent by climate (Rosenzweig *et al.*, 2002). Organisms become pests when they compete with or prey upon crop plants to an extent that reduces productivity. Not only does climate affect the type of crops grown and the intensity of the pest problems, it affects the pesticides often used to control or prevent outbreaks (Chen and McCarl, 2001; Coakley *et al.*, 1999). The intensity of rainfall and its timing with respect to pesticide application are important factors in pesticide persistence and transport.

Because of the extremely large variation of pest species' responses to meteorological conditions, it is difficult to draw overarching conclusions about the relationships between pests and weather. In general, however, most pest species are favored by warm and humid conditions. But crop damages by pests are a consequence of the complex ecological dynamics between two or more organisms and therefore are very difficult to predict. For example, dry conditions are unfavorable for sporulation of fungi, but are also unfavorable for the crop; a weak crop during a drought is more likely to become infected by fungi than when it is not stressed. Pest infestations often coincide with changes in climatic conditions, such as early or late rains, drought, or increases in humidity, which in themselves can reduce yields. In these circumstances, accurately attributing losses to pests can be difficult.

Most analyses concur that in a changing climate, pests may become even more active than they are currently, thus posing the threat of greater economic losses to farmers (Rosenzweig *et al.*, 2002). While the majority are invasive species from temperate zones, many of the worst weeds in temperate regions originated in tropical or subtropical regions, and in the current

climate their distribution is limited by low temperature. Such geographical constraints will be removed under warmer conditions. Warmer temperature regimes have been shown to increase the maximum biomass of three grass weeds significantly (Patterson, 1993). In crop monocultures, undesirable competition is controlled through a variety of means, including crop rotations, mechanical manipulations (e.g., hoeing), and chemical treatment (e.g., herbicides).

With temperatures within their viable range, insects respond to higher temperature with increased rates of development and with less time between generations (very high temperatures reduce insect longevity). Warmer winters will reduce winterkill, and consequently there may be increased insect populations in subsequent growing seasons. With warmer temperatures occurring earlier in the spring, pest populations will become established and thrive during earlier and more vulnerable crop growth stages. Additional insect generations and greater populations encouraged by higher temperatures and longer growing seasons will require greater efforts of pest management.

Warmer winter temperature will also affect those pests that currently cannot overwinter in high-latitude crop regions but do overwinter in lower-latitude regions and then migrate to the crops in the following spring and summer. Since warmer temperature will bring longer growing seasons in temperate regions, this should provide opportunity for increased insect damage.

Drought stress tends to bring increased insect pest outbreaks, so insect damage may increase in regions destined to become more arid. If climate becomes warmer and drier as well, the population growth rates of small, sap-feeding pests may be favored.

Higher temperature and humidity and greater precipitation, on the other hand, are likely to result in the spread of plant diseases, as wet vegetation promotes the germination of spores and the proliferation of bacteria and fungi, and influences the lifecycle of soil nematodes. In regions that suffer greater aridity, however, disease infestation may lessen, although some diseases (such as the powdery mildews) can thrive even in hot, dry conditions as long as there is dew formation at night.

C. Climate Change and Biotechnology

The prospect of a changing climate, caused by augmented atmospheric constituents, may provide motivation for the use of biotechnology (Rosenzweig, 2001). There may be opportunities for optimizing photosynthetic and stomatal conductance responses to higher levels of atmospheric carbon dioxide. Biotechnology techniques may offer the potential for creating effective adaptations to changing climatic circumstances. Enhanced heat and

drought tolerance of both crops and livestock are likely to be required, as are strategies to cope with shifting and newly emerging weeds, pests, and plant diseases. Finally, improved mitigation options could also be developed in regard to the ability of crops to sequester carbon, production of biofuels, reduction of methane emissions from rice-growing and ruminant livestock systems, and management of nitrous oxide emissions from nitrogen fertilization.

Several cautions are in order. Genetically modified organisms may not be able to cope with all of the effects of dynamic climate changes that occur in agricultural regions. For example, severe flooding may continue to be detrimental to crop production, regardless of genetic resources. Dissemination of new and severe crop pests may be so rapid as to bring large damages before development of appropriately modified crops. Finally, much research and testing of genetically modified crops is required, in any case, so that potential benefits and harms are more clearly understood.

VIII. CONSERVING BIODIVERSITY AND SUSTAINING FOOD PRODUCTION

Instead of the often-favored reductionist approach, which treats the production of food livestock without regard to ecological relationships, new agro-ecosystem approaches strive to integrate farming and food production units into the larger environmental domain, which recognizes and preserves the role of native fauna and flora in their natural habitats. A more holistic approach to the integration of farming and ecology will better promote nutrient recycling, biological pest and disease control, pollination, soil quality maintenance, water-use efficiency, and carbon sequestration, as well as appropriate responses to weather anomalies (droughts and floods) and to off-site (along with on-site) effects of agricultural activities.

Differences among genomes can be of great value to agriculture, and the wider the spectrum of those differences, the greater their potential uses. Therefore, every effort must be made to preserve the full variety of genetic differences among species, as each species plays an ecological role in its own niche or habitat, and interacts with all other forms of life sharing the same community or ecosystem.

Conservation of genetic resources is thus a keystone of the agro-ecosystem approach—in order to ensure the broadest array of agricultural species and the myriad biota, such as soil organisms and pollinators, which provide services that enable food production and harvesting. Facilities such as germplasm banks need to be expanded and improved so that genetic

resources for both crops and livestock are preserved. Germplasm collections should include the widest possible array of varieties and breeds, as well as their wild relatives. Both *in situ* and *ex situ* collections should be protected. All collections should be registered in a common, accessible database for the benefit of breeders and farmers everywhere. The effort must include the various international agencies (with coordination and networking among such groups as the CGIAR, World Bank, USAID, NGOs, United Nations FAO, UNEP, and UNESCO), as well as national agricultural agencies. The rights of developing countries to their indigenous genetic resources should be respected and not be appropriated by outside commercial interests. Access to such resources should be freely available and fairness in rights should be assured.

Knowledge of soil biota is important because they are linked to critical ecosystem processes that sustain life. Research needs include the role of soil biodiversity in plant health and ecosystem processes and linkages with other aquatic and terrestrial systems if we are to understand how to manage ecosystems for food production sustainably. Globally, soil degradation has accelerated as human populations have expanded, threatening the stability of Earth's ecosystems, both natural and managed. Determining how soil species diversity will change under disturbances, such as increasing land use, will help scientists, policymakers, and managers devise and implement strategies to preserve and maintain our terrestrial ecosystems and our food production base for the long term.

The enhanced greenhouse effect is expected to result in significant global warming during the course of this century. The potential impacts of climate change and climate variability on biodiversity need to be more fully characterized, since both agricultural and natural ecosystems will thereby be affected. The zonation and adaptation of species will shift as the temperature and hydrological regimes change. Improved methods of assessing biodiversity in relation to climate change need to be developed.

The formulation and implementation of biodiversity policies is a global priority. National and international policies are needed to encourage the adoption on a wide-scale of the agro-ecosystem paradigm and thus the conservation of biodiversity in food-producing systems. This will ensure nutritious food for the still-growing population, minimize exposure to agricultural chemicals, and promote both human and ecosystem health in an integrated way.

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THE DEPTH DISTRIBUTION OF SOIL ORGANIC CARBON IN RELATION TO LAND USE AND MANAGEMENT AND THE POTENTIAL OF CARBON SEQUESTRATION IN SUBSOIL HORIZONS

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Routine soil surveys for estimating the soil organic carbon (SOC) pool account for a soil depth of about 1 m. Deeper soil horizons, however, may have a high capacity to sequester significant amounts of SOC as the turnover time and chemical recalcitrance of soil organic matter (SOM) increases with depth. The subsoil carbon (C) sequestration may be achieved by higher inputs of fairly stable organic matter to deeper soil horizons. This can be achieved directly by selecting plants/cultivars with deeper and thicker root systems that are high in chemical recalcitrant compounds like suberin.

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Furthermore, recalcitrant compounds could be a target for plant breeding/biotechnology to promote C sequestration. A high surface input of organic matter favors the production of dissolved organic carbon that can be transported to deeper soil horizons and thus contribute to the subsoil C storage. By promoting the activity of the soil fauna, organic matter can be transferred to deeper soil layers and stabilized (e.g., in earthworm casts). Manipulating the subsoil microorganisms may result in higher amounts of fairly stable aliphatic compounds. The subsoil below 1-m depth may have the potential to sequester between 760 and 1520 Pg C. These estimates are, however, highly uncertain and more studies on C storage in subsoil horizons and the assessment of the chemical nature of subsoil organic C are needed.

I. INTRODUCTION

Soils are the largest terrestrial pool for organic carbon in the biosphere. Large-scale changes in land use like deforestation and agricultural activities, including biomass burning, plowing, drainage, and low-input farming have resulted in significant changes in soil organic carbon (SOC) pools (Lal, 2003). By mineralization, leaching, erosion, or change in land use, 50–70% of the antecedent SOC is lost as CO_2. Thus, world soils historically have been a major source of atmospheric enrichment of CO_2, although uncertainties in the statistics exist. About 20% of the global emissions presently come from land use change (IPCC, 2001).

Information on global and regional SOC pool is available (e.g., Eswaran *et al*., 1993; Batjes, 1996). However, data on vertical distribution of the SOC pool in relation to vegetation and land use is scanty (Jobbágy and Jackson, 2000). It is widely accepted that soil organic matter (SOM) is largely concentrated in the top 30 cm of the soil, but there is growing evidence that deeper soil horizons have the capacity to sequester high amounts of SOC despite the concentrations in the subsoil (Jobbágy and Jackson, 2000; Liski and Westman, 1995; Richter and Markewitz, 1995; Swift, 2001). One reason for the uncertainty is that the usual fixed depth of about 1 m is generally considered adequate in routine soil surveys. That being the case, the magnitude of underestimation of the global SOC budget remains to be speculative.

Land use changes, however, may affect the SOC storage in deeper soil horizons. For example, by comparing data from 74 publications, Guo and Gifford (2002) observed that conversions of forest land to pasture or crop land had no effect on SOC stocks below 1 and 0.6-m depth, respectively. In contrast, conversion of crop land to pasture caused substantial C accumulation below 1-m depth. However, conclusions on the effects of land use

changes on soil C stocks are hampered by the small global database. For example, among 78 studies on the effects of conversion from forest to agricultural land only 2 studies reported stores below 1-m soil depth (Murty *et al*., 2002).

Information is also scanty about the contribution of above-ground vs. below-ground residues to the amount of C sequestered in the subsoil (Follett, 2001). The knowledge of SOC distributions and the controls on C sequestration within soil profiles are used to predict the effects of land use changes on the C emission (Jobbágy and Jackson, 2000). The importance of SOC sequestration in subsoils mitigating the greenhouse effect is related to the increase in turnover time of SOM with increases in depth, and to the fact that subsoil SOC occurs in fairly stable and most probably highly recalcitrant forms to biodegradation (Batjes, 1996; Kögel-Knabner, 2000; Nierop and Verstraten, 2003).

This review article collates and synthesizes the available literature on the vertical distribution of SOC in relation to principal C sources, describes changes in quality and quantity of C with soil depth, and discusses differences in SOC pool in relation to land use. The focus is not on collecting the information on the stabilization of SOC in subsoil horizons by physical protection through aggregate formation (Six *et al*., 2004), but to review the literature on the chemical recalcitrance as the only mechanism by which SOC can be protected over long periods of time (Krull *et al*., 2003). Potential strategies to enhance the subsoil C sequestration by management practices are also discussed.

II. SOURCES AND DYNAMICS OF SOIL ORGANIC CARBON WITHIN SOIL PROFILES

A. Plant Litter as the Principal Source of Soil Organic Matter Formation

Plant litter is the primary source of SOC formation while microbial residues are secondary sources (Kögel-Knabner, 2002; Krull *et al*., 2003). The relative contribution of animal residues as precursor of humus in soil is rather small (Wolters, 2000). Plant litter consists of intracellular and storage materials and cell wall components. Refractory plant derived biomacromolecules that are relatively resistant to biodegradation and selectively concentrated in SOM are extremely important to the potential of C sequestration by management (Fig. 1; Derenne and Largeau, 2001). In general, leafy plants decompose faster than woody plants, and leaves faster than roots (Wang *et al*., 2004).

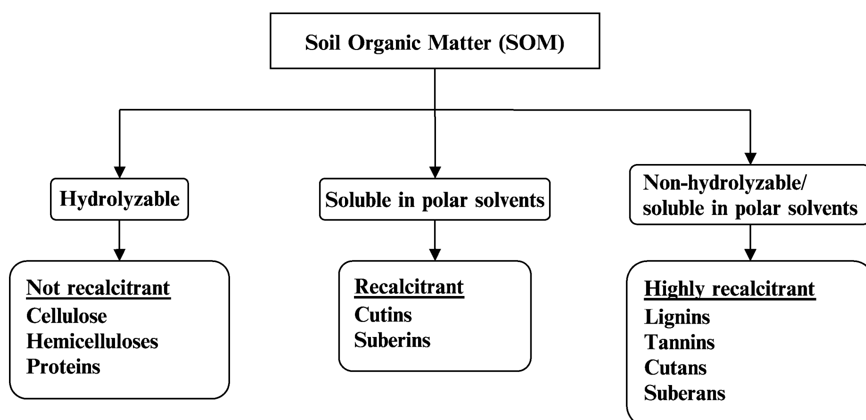


Figure 1 Plant litter biomacromolecules as precursors of soil organic matter.

Proteins are abundant in plant cells and probably less stable in the soil, but peptide type compounds are stabilized in SOM over long periods (Knicker *et al.*, 1993). The most abundant plant biopolymer is cellulose which decomposes slowly aerobically but is relatively enriched under anaerobic conditions (De Leeuw and Largeau, 1993; Martin and Haider, 1986). In contrast, higher decomposition rates are observed for the non-cellulosic polysaccharides, hemicelluloses and pectin (Swift *et al.*, 1979). The second most abundant biopolymers are lignins which are largely contributing to terrestrial biomass residues. These compounds exhibit a higher resistance to microbial degradation compared to celluloses, and are virtually resistant under anaerobic conditions (Haider, 1992). Tannins are also abundant constituents of terrestrial plants, and the proanthocyandins are important potential sources of refractory material in soils and contribute to the formation of humic substances (Derenne and Largeau, 2001). Important components of soil lipids which represent a relatively stable C pool are already found in plant lipids (Kögel-Knabner, 2002). The fate of decomposition products from chlorophyll and other pigments and their relevance to humus formation is largely unknown. The non-hydrolyzable cutans and suberans are also common components of higher plants (Bernards, 2002; Heredia, 2003). Their preservation in soils and contribution to the recalcitrant aliphatic fraction of SOM is, however, debatable (Augris *et al.*, 1998). Suberin is mostly found in root tissues but also in aboveground parts of woody tissues and is a major contributor to the SOM (Bull *et al.*, 2000; Nierop *et al.*, 2003).

Data on the contribution of recalcitrant biomacromolecules to plant residues are highly variable as conventional methods are generally not specific enough (Rahn *et al.*, 1999; Kögel-Knabner, 2002). In general, forest litter is higher in lignin due to woody tissues while crop residues are higher in

polysaccharides (cellulose and hemicellulose; Table I). Only 50–60% of the total organic C in plant litter is accounted for by chemical degradative techniques.

The composition of plant materials can be deduced from solid–state ^{13}C NMR spectra and molecular level information from analytical pyrolysis or (thermo) chemolysis (Kögel-Knabner, 2002). The solid–state ^{13}C NMR spectra of aboveground beech (*Fagus sylvatica* L.) litter is dominated by signals from polysaccharides (cellulose and hemicelluloses) and lignin, and alkyl C from lipids and cutins. The ^{13}C NMR spectra of straw from wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.) and rye (*Secale cereale* L.) as well as hay are all dominated by polysaccharides while aromatic C, essentially lignin, and alkyl-C (lipids, cutins, peptides) are lower than in forest litter (Fründ and Lüdemann, 1989; Rowell *et al*., 2001). The main components of corn (*Zea mays* L.) leaves are polysaccharides, lignin, lipids, and alkyl-aromatics (Gregorich *et al*., 1996; Poirier *et al*., 2003).

Carbon-13 CP/MAS NMR spectroscopy indicates that oilseed rape (*Brassica napus* L.) shoots and roots contain comparable high amounts of cellulose and hemicellulose C (Trinsoutrot *et al*., 2001). Signals from lipids and cutin, and essentially from peptides are prominent in the spectrum of ryegrass (*Lolium perenne*) leaves (Kögel-Knabner, 2002). The ^{13}C NMR spectra indicate that polysaccharides and aromatic components dominate in the roots of beech (Table I). Corn roots contain a wide range of fatty acids beside carbohydrates, lignin, lipids and alkyl-aromatics (Gregorich *et al*., 1996). Oilseed rape roots are higher in aromatic and phenolic C compared to shoots (Trinsoutrot *et al*., 2001). Wheat roots are higher in aryl and O-aryl C (mainly from lignin and polyphenols) but lower in alkyl C than wheat straw (Wang *et al*., 2004). The NMR spectra indicate that the roots of grasses are high in polysaccharides and low in lignin and suberins. Little information exists on the composition of aliphatic biopolymers like cutin and suberin from agricultural crops. Furthermore the composition of the components of different plant parts may be variable (Nierop *et al*., 2001).

B. Differences Between Above- and Below-Ground Plant Residues

The composition of the above-ground C input may be substantially different to the below-ground input (Kögel-Knabner, 2002; Rasse *et al*., 2004). The above-ground input in forests consists mainly of leaf and needle litter but branches, bark and fruits also contribute to the litterfall. In addition, woody debris is an important component of the OM input in natural forests whereas herbaceous litterfall is of minor importance in forests. There is relatively less information available on the above-ground C input for arable and grassland ecosystems. However, C inputs depend on

Table I
Main Biomacromolecules in Plant Litter

Species	Source	Cellulose (%)	Lignin (%)	Reference
Alfalfa (*Medicago sativa* L.)	Stem	13–33	6–16	Scheffer (2002)
Beech (*Fagus sylvatica* L.)	Wood	32	24	Scheffer (2002)
	Bark	38	39	Scheffer (2002)
	Leaves	20	11–16	Scheffer (2002)
	Roots	33	22	Scheffer (2002)
	Fine roots	19	33	Scheffer (2002)
Brussels sprouts (*Brassica oleracea var. gemmifera* Zenker)	Crop residue	21	7	Rahn *et al.* (1999)
Corn (*Zea mays* L.)	Leaves	35	3	Fernandez *et al.* (2003)
	Stems	41	6	Fernandez *et al.* (2003)
	Coarse roots	45	10	Fernandez *et al.* (2003)
	Fine roots	49	12	Fernandez *et al.* (2003)
Millet (*Pennisetum americanum* L.)	Plants	29–37	9–13	Bilbro *et al.* (1991)
Potato (*Solanum tuberosum* L.)	Crop residue	23	9	Rahn *et al.* (1999)
Red beet (*Beta vulgaris var. vulgaris* L.)	Crop residue	13	3	Rahn *et al.* (1999)
Rice (*Oryza sativa* L. (Cult.))	Straw	35–37	11–13	Devêvre and Horwáth (2000)
Ryegrass (*Lolium perenne* L.)	Shoots	19–26	4–6	Scheffer (2002)
	Leaves	22	2	Fernandez *et al.* (2003)
	Roots	30	9	Fernandez *et al.* (2003)
Sorghum (*Sorghum bicolor* (L.) Moench)	Green manure	30–31	3–4	Clément *et al.* (1998)
Soybean (*Glycine max* (L.) Merr.)	Green manure	24–27	7–8	Clément *et al.* (1998)
Spruce (*Picea abies* L.)	Wood	40	28	Scheffer (2002)
	Bark	48	38	Scheffer (2002)
	Needles	15	14–20	Scheffer (2002)
Wheat (*Triticum aestivum* L.)	Straw	27–33	18–21	Scheffer (2002)
	Crop residue	39	12	Rahn *et al.* (1999)

the amount and type of crop residues and fertilizer application, and are much higher if the crop residues are returned to the soil.

The below-ground C input as root litter and rhizodeposition considerably contributes to SOM (Fernandes *et al.*, 1997). Roots contribute more C to SOM than aboveground residue (Wilhelm *et al.*, 2004). Annual C inputs from fine roots frequently equal or exceed those from leaves (Jackson *et al.*, 1997). This can occur to great depths and transfers C deep into subsoil horizons with a global average maximum rooting depth of 4.6 m (Canadell *et al.*, 1996; Nepstadt *et al.*, 1994; Trumbore *et al.*, 1995). While tundra, boreal forests, and temperate grasslands have 80–90% of their roots in the upper 30 cm, deserts and temperate coniferous forests have only 50% of their roots up to this depth (Jackson *et al.*, 1996).

The organic C released by living roots (i.e., the rhizodeposition) accounts for a substantial input of OM in soils. Rhizodeposition can lead to C accumulation or consumption by altering the decomposition rate of SOM (Kuzyakov, 2002; Kuzyakov *et al.*, 2000). Pastures have a higher below-ground allocation compared to wheat due to a longer vegetation period (Kuzyakov and Domanski, 2000). Rhizodeposition by corn is reportedly 3 times greater than suggested previously (Allmaras *et al.*, 2000). For the amount of rhizodeposition under forests, only limited data are available and no generalization can be made.

With respect to C sequestration in the subsoil, the lower biodegradability of plant roots and the root-to-shoot ratios of different vegetation types are highly relevant. The lower degradability of roots can be attributed to their higher lignin content compared to shoots as lignin is supposed to be chemically recalcitrant (Tegelaar *et al.*, 1989; Table II). Beside lignin, higher tannin contents and less readily decomposable compounds in roots compared to shoots probably contribute to the lower decomposition rate of roots (Beuch *et al.*, 2000; Kraus *et al.*, 2003; Waid, 1974). However, these data may not be reliable due to analytical uncertainties (e.g., Preston *et al.*, 1997). Furthermore the relative decomposition rates between the above- and below-ground parts may differ with the plant species (Wang *et al.*, 2004). More than half of all SOM still remains uncharacterized at the molecular level (Hedges *et al.*, 2000). The available data on root:shoot ratios of different vegetation types and plant species are also highly variable (Table III). Under similar climatic conditions, grassland and steppe soils generally receive a higher proportion of total C input as root litter compared to forest and cropland.

C. Specific Microbial Precursors of Soil Organic Matter

Major recalcitrant biomacromolecules as precursors of SOM formation may also be derived from the microbial biomass (Hedges *et al.*, 2000). The fungal cell wall contains the highly crystalline, non-water soluble

Table II
Lignin in Root and Shoot Tissues

Plant	Lignin (%) Roots	Shoots	Reference
Wheat	9–12	7–9	Dignac *et al.* (2005); Wang *et al.* (2004)
Corn	10	7	Dignac *et al.* (2005)
Hairy vetch (*Vicia villosa* Roth subsp. *Villosa*)	17	5	Puget and Drinkwater (2001)
Ryegrass	15	6	De Neergard *et al.* (2002)
Clover	19	8	De Neergard *et al.* (2002)

Table III
Root-to-Shoot Ratio in Different Vegetation Types and Crops

Source	Root-to-shoot ratio	Reference
Steppe	6–13	Kögel-Knabner (2002)
Tundra	6.6	Kögel-Knabner (2002)
Grassland	0.3–6	Kögel-Knabner (2002)
Forests	0.2–4	Kögel-Knabner (2002)
Corn	0.21–0.25 (0.35–0.38 incl. rhizodeposits)	Allmaras *et al.* (2004)
Wheat	0.28 (0.48 incl. rhizodeposits)	Allmaras *et al.* (2004)
Soybean	0.23 (0.38 incl. rhizodeposits)	Allmaras *et al.* (2004)
Oats	0.4	Bolinder *et al.* (1997)
Barley	0.5	Bolinder *et al.* (1997)

polysaccharides chitin and β-glucan (Kögel-Knabner, 2002). Fungi also synthesize lipids and melanins, although to a minor extent. The non-hydrolyzable melanins protect fungal cells against microbial attack and are possible precursors of humic substances (Butler and Day, 1998; Saiz-Jimenez, 1996). The arbuscular mycorrhiza occurs in about 80% of plant species (Strack *et al.*, 2003). Arbuscular mycorrhizal hyphae contain significant amounts of the iron-containing glycoproteinaceous substance glomalin that may contribute to the recalcitrant soil C fraction (Rillig *et al.*, 2003; Treseder and Allen, 2000). The ectomycorrhiza in woody trees receive most of the C allocated to the belowground biomass whereas the roots mainly serve as a transport tissue for carbohydrates (Steinmann *et al.*, 2004).

Bacterial cell wall polysaccharides are relatively easily decomposed, but their basic units glucosamine, galactosamine or muramic acid are found in hydrolysis residues of soils and accumulate during litter decomposition (Stevenson, 1994; Coelho *et al.*, 1997). Bacterans are insoluble, non-hydrolyzable aliphatic biomacromolecules present in substantial amounts in bacteria. They have a

high potential to accumulate in soils and are potential precursors for aliphatic components of SOM (Augris *et al.*, 1998). The few published analyses of the microbial biomass using ^{13}C NMR spectroscopy indicate that bacterial biomass differs distinctly from fungal biomass as fungi are higher in O-alkyl and lower in alkyl C (Baldock *et al.*, 1990).

D. The Stabilization of Plant Derived Compounds and Soil Organic Matter

Several stabilization mechanisms are responsible for protection of plant residues and their decomposition products in the soil against microbial attack, and facilitate accumulation of humic substances (Sollins *et al.*, 1996). Biochemical stabilization is promoted by the complex chemical composition of the organic matter (Cadisch and Giller, 1997). The chemical recalcitrance can either be an inherent property of the plant litter (e.g., due to recalcitrant compounds like lignin, tannin, cutin, suberin) or can be attained through condensation and complexation reactions during decomposition resulting in the accumulation of stable aromatic and long chain aliphatic compounds (Paul *et al.*, 1997). The physicochemical stabilization is the result of chemical or physicochemical binding between plant litter compounds and SOM, and soil minerals such as clay and silt particles (Six *et al.*, 2002). The glycoprotein glomalin produced mainly by hyphae of arbuscular mycorrhizal fungi might also be involved in stabilization of aggregates (Rillig *et al.*, 1999; Wright and Upadhyaya, 1998). The type of clay probably also plays an important role, as example 1:1 and 2:1 clays have substantial differences in CEC and specific surface tentatively resulting in different adsorption capacities for organic materials. The Fe- and Al-oxides have contrasting effects on the physicochemical stabilization as they can reduce the available soil mineral surface for adsorption of SOM but also co-flocculate SOM and consequently stabilize it (Wiseman and Püttmann, 2004). The availability of organic C for microbial decomposition is reduced by inclusion of OM within soil aggregates (Golchin *et al.*, 1994). Physical protection by aggregates is a consequence of the separation between microbes and enzymes and their substrates (i.e., organic matter) as is indicated by the positive influence of aggregation on SOM accumulation (Six *et al.*, 2002).

E. Translocation of Organic Matter to Subsoil Horizons

In the course of the decomposition of plant material water soluble intermediates are released into the soil solution where they present a major portion of the dissolved organic matter (DOM) beside compounds released by microorganisms (Guggenberger *et al.*, 1994). Another major source of

water-soluble C is humus (Gregorich *et al*., 2003). Contradictory to the widespread assumption, Kalbitz *et al*. (2003) found no evidence that DOM represents the most biodegradable pool of SOM. The DOM is transported in soil profiles and with increasing depth strongly adsorbed to mineral surfaces resulting in reduced decomposition of organic C (Baldock and Smernik, 2002; Kaiser and Guggenberger, 2000; Kalbitz *et al*., 2000). Sorption to the mineral phase in subsoils may be more effective than in topsoils because mineral surfaces are not yet saturated with OM (Rasse *et al*., 2004). In forest mineral soils DOM can contribute to stable C due to high DOM fluxes and a mean residence time up to 12.5 years (Kalbitz *et al*., 2003).

The soil fauna (i.e., earthworms, ants, and termites) are capable to dig burrows several meters deep into the soil (Benckiser, 1997; Wolters, 2000). While the importance of earthworms in soil systems has long been recognized, little quantitative information is available about the role of termites (Lee and Foster, 1991). Qualitatively, polysaccharides are lost preferentially and lignin accumulated in wood-feeding termites, and some evidence for polysaccharide loss in soil-feeding termites is indicated (Hopkins *et al*., 1998). Within earthworm burrows formed by anecic species, significant amounts of OM are translocated to the subsoil by covering the inner surface of the burrows with middens—accumulations of raw and decomposed plant residues, casts, and soil (Nielsen and Hole, 1964). The casts are a product of the digestion of organic substrates with soil minerals in their gut (Shipitalo *et al*., 1994; Shuster *et al*., 2001). The organic C in these casts is mainly physically stabilized and earthworms may alter the size and dynamics of the microaggregate-protected SOM pool (Binet and LeBayon, 1999; Guggenberger *et al*., 1996; Lavelle, 1988; Whalen *et al*., 2004). The stability of earthworm casts is high especially in the subsoil (Ge *et al*., 2001). In regions of high animal activity, recalcitrant SOM is enriched, at least temporarily (Wolters, 2000). Earthworms produce a more even distribution of OM in the soil profile. However, what proportion of earthworm casts are deposited in the soil profile under field conditions is not known (Whalen *et al*., 2004). Endogeic earthworm species which live in mineral soil horizons are considered major agents of aggregation and SOM stabilization (Lavelle and Spain, 2001). Earthworm activity may be of great significance for the long-term stabilization of SOM (Bossuyt *et al*., 2004).

III. DEPTH DISTRIBUTION OF SOIL ORGANIC CARBON AND ROOTS

The storage of SOC in the soil depends on the balance between additions and losses of C (Sollins *et al*., 1996). Biotic controls like the abundance of faunal, microbial, and plant species, and environmental controls like

temperature, moisture, and soil texture influence stabilization and destabilization processes of SOC. The C storage varies mainly as a result of climatic, geological and soil-forming factors in the long-term, whereas vegetation and changes in land use patterns affect storage in the short-term (Batjes, 1996). Global estimates of the SOC pool to 2-m soil depth in tropical regions were lower than for soils from all other regions. The highest SOC concentrations were observed in the upper soil layers, but large amounts are also stored between 1- and 2-m depth (Batjes, 1996). Any disturbance and relocation of SOC is, therefore, fundamental to the global C balance (Moiser, 1998). The knowledge of the key factors determining long-term SOC storage, however, is still limited (Neff *et al*., 2002).

The SOC pool and its dynamics with regards to climate and texture with soil depth are not understood (Jobbágy and Jackson, 2000). Without additions of external C, the radiocarbon age of the OM reflects the mean residence time and thus the radiocarbon age is a measure of stability (Rumpel *et al*., 2002). Consequently, the stability of SOM significantly increases with depth along with the radiocarbon age (Paul *et al*., 1997). At depth, chemical interactions are probably more important than physical processes in stabilization of SOC, while aggregation has its strongest effects in the surface horizons (Paul *et al*., 2001).

A. Depth Distribution of Roots

On a regional scale, plant allocation above- and below-ground is probably the major determinant of the relative distribution of SOC with depth (Jobbágy and Jackson, 2000). Above-ground OM has probably only limited effects on SOM levels compared to below-ground OM as has been demonstrated by long-term residue management studies (Campbell *et al*., 1991; Clapp *et al*., 2000; Reicosky *et al*., 2002). The dominant role of root C in soil is also indicated by higher relative contributions of root vs. shoot tissues to the SOC pool estimated by Rasse *et al*. (2004), based on datasets from a variety of *in situ* and incubation experiments. Vegetation types differ in their vertical root distribution leaving distinct imprints on the depth distribution of SOC. The depth to which 95% of root biomass occurs is the lowest for grasses, highest for shrubs, and intermediate for trees (Table IV; Jackson *et al*., 1996, 1997). The average maximum rooting depth for trees and shrubs is considerably deeper than for grasses and herbs (Canadell *et al*., 1996). Root depths up to 40 m have been reported for *Eucalyptus marginata* in southern Australia, 18 m for woody plants in the Brazilian cerrado, and 25 m for *Quercus fusiformis* at the Edwards Plateau, central Texas (Jackson *et al*., 1999, 2000).

Forests may have shallower SOC profiles compared to grasslands as indicated by differences in root-to-shoot ratios (Table III). The remaining

Table IV
Global Root Biomass Distribution, Rooting Depths, and SOC Storage

	Grasslands/ Grasses	Shrublands/ Shrubs	Forests/ Trees	Reference
95% of the root biomass	top 0.6 m	top 1.35 m	top 1.0 m	Jackson *et al.* (1996, 1997)
Maximum rooting depth	2–2.5 m*	7 m	5 m	Canadell *et al.* (1996)
SOC storage between 1–3 m relative to the amount stored in the top 1 m	43%	77%	56%	Jobbágy and Jackson (2000)

*grasses and herbs

roots at greater depth, however, may be important for SOC stocks in subsoil horizons. For example, Gill and Burke (2002) observed that the decomposition rate of *Bouteloua gracilis* roots at 1-m depth was 50% slower than at 0.1-m depth, with estimated residence times of 36 and 19 years, respectively. The C loss rates from roots decreased linearly with depth. Based on the global biogeography of roots, Schenk and Jackson (2002) estimated that most profiles had 95% of all roots in the upper 2 m but the remaining 5% may reach much greater depths. By comparing 14 profiles containing both woody and grass roots, six profiles had equal depths for 95% of the roots from woody plants and grass, in three profiles woody plants rooted deeper, and in five profiles grasses rooted deeper than woody plants. Further rooting depths varied greatly among sites. The models developed by Schenk and Jackson (2002) for estimating rooting depth accounted for at most 50% of the observed variance. Cairns *et al.* (1997) reported that 65% of global root biomass inventories in forest ecosystems did not include the sampling depth, and only 15% sampled below 1 m. Yet, it was assumed that investigators captured practically all roots.

B. Depth Distribution of Soil Organic Carbon Based on Estimates

The amount of C stored in Histosols below 1-m depth is probably significant as the actual depth of these organic soils is much greater than 1 m (Eswaran *et al.*, 1993). Batjes (1996) estimated that Histosols contain 65% of their SOC to 2 m between 1- and 2-m depth. Large amounts of SOC lie also below 1 m in both mineral and organic soils including Acrisols, Gleyic and Humic Cambisols, Ferralsols, Humic Gleysols, Thionic Fluvisols, Nitosols, Humic Podzols, Mollic Andosols, and Vertisols. For

Histosols and Podzols, however, discrepancies in SOC stocks exist for the second meter in estimates reported by Batjes (1996) and Jobbágy and Jackson (2000). Such discrepancies contribute to uncertainty in estimates of C storage in deep soil layers of the boreal regions for which there are almost no SOC data below 1-m depth.

The amount and vertical distribution of OM in boreal, temperate, tropical, and subtropical soils probably vary distinctively with depth (Batjes, 1998). Batjes (1996) estimated that in peat soils reserves of C stored globally between 1 and 2 m are more than the reserve stored up to 1-m depth. Most soils store 37–39% of their total SOC to 2 m between 1 and 2-m depth. The SOC is more deeply distributed in arid shrublands than in arid grasslands, and subhumid forests have shallower SOC distribution than subhumid grasslands (Jackson *et al*., 2000). Forty-three percent of SOC in the top meter of shrublands was found between 40 and 100 cm, but only 34% of SOC in grasslands was found within this depth.

For the first time, estimates of SOC pool to 3-m depth in soil profiles associated with natural vegetation have been reported by Jobbágy and Jackson (2000). All profiles with potential effects on the vertical distribution of SOC were, however, excluded from the analysis (e.g., agricultural soils disturbed by plowing). Shrublands and forests store more SOC in the second and third meters than grasslands relative to the SOC storage until 1-m depth (Table IV). Separated by biomes, deserts, tropical deciduous forests, tropical grasslands/savannahs, sclerophyllous shrubs, temperate grasslands, and crops had more than 50% of the amount of SOC until 1 m in the second and third meters. Globally more C than that contained in the atmosphere is stored between 1 and 3 m below the soil surface. Global totals for the second and third meters indicated that tropical evergreen forests and tropical grasslands/savannahs store most SOC between 1- and 3-m depth.

C. Depth Distribution of Soil Organic Carbon Based on Soil Data

The world database for a meta analysis on soil C stocks is quite small (Guo and Gifford, 2002). Furthermore, measurements of SOC at depths greater than 1 m are rare. In temperate climates, large amounts of SOC are probably stored in B and C horizons. In a Dystric Cambisol under spruce (*Picea abies* [L.] Karst.), however, the soil between 1 and 1.4 m accounted only for 1.8% of the SOC contained in the mineral soil, with increasing contribution of ancient, stabilized C with depth (Rumpel *et al*., 2002). The SOC pool between 1- and 1.1-m depth contributed 5.9% of the total SOC pool until 1.1 m in an abandoned grazed mixed grass prairie in Canada,

whereas the same increment contributed only 4.4% in the adjacent native mixed grass prairie (Henderson *et al.*, 2004). However, considerable vertical variations in SOC were observed in this study. In a clayey soil from an agricultural field in Iowa, the SOM contents between 1 and 1.3 m were reduced by 85% compared to the top 0.3 m, and further reduced by 9% between 2.7 and 3 m (Taylor *et al.*, 2002). However, in a sandy soil from Michigan, no difference in SOM contents between 1–1.3 m and 3.9–4.2 m were observed. Mikhailova *et al.* (2000) studied effects of cultivation on SOC stocks in chernozem soils in Russia. In the native grassland, 13% of the total SOC to 1.3-m depth was stored between 1 and 1.3 m. In the soil profile of the annually cut hay field, 8% of the total SOC was stored between 1 and 1.25 m, whereas 8% was stored between 1 and 1.18 m at the continuously cropped field, and between 1 and 1.2 m of the 50-year continuous-fallow field. The SOC concentrations below 1–1.2 m up to 2.3-m depth at the grassland, hay and cropped fields were higher compared to the fallow field. The SOC contents in B horizons (0.9–1.7 m) of four Ferralsols in Brazil accounted for 13–44% of the C content in A horizons (0–33 cm) (Gonçalves *et al.*, 2003). In soils of eastern Amazônia, SOC contents in the upper meter dropped off steeply; however, the large volume of deep soil (1–8 m) contained 60% of the total C inventory of forest, degraded pasture, and managed pasture soils to 8-m depth (Trumbore *et al.*, 1995). Three profiles in primary forests of Amazônia stored 28–30 % of their total SOC to 2.1 m between 1 and 2.1 m depth (Telles *et al.*, 2003). In a sandy soil in north-eastern Australia, Bird *et al.* (2003) found appreciable SOC densities below 1 m and up to 2.5-m depth.

Urban soils in Germany contain considerable amounts of SOC below 1-m depth (Beyer *et al.*, 2001; Lorenz and Kandeler, 2005; Wu *et al.*, 1999). Pouyat *et al.* (2002) reported relatively high C amounts in urban soils to 1-m depth due to increase in below-ground productivity. The SOC storage at depth in urban ecosystems, however, is highly variable and affected by physical disturbances, burial of soil by fill and carbonaceous parent materials like debris, ash, slag, garbage, and sewage sludge, also partially from the deposition of airborne particles, and soil management inputs (Pouyat *et al.*, 2002). These materials frequently contain elemental C, which is usually considered highly resistant (Currie *et al.*, 2002; Derenne and Largeau, 2001). The SOM in industrialized urban areas may, therefore, consist of a mixture of natural humic substances and anthropogenic organic particles (Kögel-Knabner, 2000). Although urban land-use conversion represents only a small proportion of the land base, changes occurring in SOC storage may probably be more persistent than in other land-use conversions. Compared to their natural counterparts, the urban soils probably show a substantially different behavior against environmental hazardous compounds and microbial activity (Beyer *et al.*, 2001).

D. Changes in the Chemical Composition of Soil Organic Carbon with Depth

For below-ground organic C inputs, only a few studies are available on the contribution of plant litter residues to the chemical composition of SOC (Kögel-Knabner, 2002). As revealed by CPMAS ^{13}C NMR spectroscopy, the composition of the below-ground C input may be substantially different from the above-ground input. Decomposition of plant litter is mostly associated with a relative increase in the content of alkyl C and a decrease in the content of O/N-alkyl C (mainly polysaccharides and proteins) while the content of aromatic C remains almost unchanged (Baldock *et al*., 1997; Scheffer, 2002). Plant litter is mainly deposited in the surface soil, thereby strongly contributing to SOM in the upper soil horizons. The extent of decomposition tends to increase with soil depth. However, root litter and the translocation of particulate OM and DOM may also affect the composition of the subsoil C (Kaiser and Guggenberger, 2000).

Within forest and arable soils, litter compounds detectable by wet chemical analysis decreased with depth, whereas humic compounds increased, and fulvic acids were translocated to deeper soil horizons (Beyer *et al*., 1992, 1993). Based on molecular-level analysis, the proportion of root-derived suberin compared to cutin increased with increase in depth in a forest soil (Nierop, 1998). Lignin could not be detected in the mineral horizon of a peaty gley soil whereas lignocellulosic material was only weakly decomposed in the overlying fermentation horizon (Huang *et al*., 1998). Lignin-derived phenols were also not detected between 0.3- and 1.7-m depth in a Luvisol (Schmid *et al*., 2001). In contrast, low amounts of lignin with a similarly low degree of decomposition were found between 0- and 0.3-m depth. The changes in the distributions of phenols and hydroxyalkanoic acids with depth in a Dystric Cambisol indicated that C derived from suberin/cutin is preferentially preserved at depth compared to C derived from lignin (Rumpel *et al*., 2004). These results were confirmed by ^{13}C CPMAS NMR spectroscopy. Furthermore, lignin was not stabilized in the mineral soil horizons. In contrast, Schmidt and Kögel-Knabner (2002) reported that in 0–14 cm and 46–91-cm depth in a Haplic Alisol under deciduous forest, most of the OM was present in O-alkyl (mainly polysaccharides) beside methylene structures, each contributing one-third to the bulk OM.

The black carbon (BC) originating from incomplete combustion of OM is generally enriched with soil depth (Glaser *et al*., 2000). Furthermore, char may be recalcitrant in soils (Baldock and Smernik, 2002; Skjemstad *et al*., 2002). Lignite-derived material was estimated to contribute significantly to SOC in forest and agricultural soils (Rumpel *et al*., 1998; Schmidt *et al*., 1996). In soil profiles under natural vegetation in Brazil, charcoal was found

from surface horizons to 2.1-m depth (Pessenda *et al*., 2001). In a chernozemic soil profile, BC remained at a high level to 1-m depth while in the reference soil, no BC was detected below 0.4 m (Kleber *et al*., 2003). The NMR spectroscopy revealed that in 40–50-cm depth of the reference soil the intensity in the alkyl region was slightly increased compared to 0–10 cm with a concomitant small increase in the aromatic C region. In contrast, the SOC in the deeper horizon of the chernozemic soil was dominated by aromatic C from the selective preservation of lignin residues but also from amendments of charred OM. By comparing a variety of German chernozemic soils, Schmidt *et al*. (1999) observed that charred OC contributed more to bulk soil C in subsurface (maximum depth 0.6 m) than in surface horizons. Furthermore, contributions from O-alkyl C decreased with depth indicating lower contributions of plant litter derived polysaccharides at depth. In the refractory (non-hydrolyzable) SOC fraction of a soil sample from 3–3.1-m depth in a ferralic tropical soil, ligneous and aliphatic materials (cutans, suberans) were absent whereas melanoidins (condensation products of amino acids and sugars) and BC particles were present (Poirier *et al*., 2002).

The soil types investigated by modern analytical techniques are rather limited (Kögel-Knabner, 2000). The qualitative changes of SOC with depth cannot, therefore, be generalized. Some results of studies based on modern analytical techniques are discussed below. In the soil profile of a Vertisol in Australia, aryl C (mainly charcoal) increased from 0 to 1.2-m depth while alkyl and O-alkyl C (polysaccharides) concomitantly decreased (Skjemstad *et al*., 2001). In contrast, in another Vertisol smaller changes in the chemical composition of SOC between 0 and 0.3-m depth were observed but OM between 0.9 and 1.2 m was dominated by alkyl C, and SOC was more decomposed in the subsoil. In a Luvisol, the changes in the relative contributions of alkyl and aromatic C to SOC were highly variable to 1.7-m depth, whereas O/N-alkyl C decreased with depth (Schmid *et al*., 2001). Carboxylic and aliphatic compounds increased with soil depth in forest and arable soils whereas polysaccharides decreased (Beyer *et al*., 1992). In soil profiles at the Hubbard Brook Experimental Forest, alkyl C increased slightly from the surface to 82-cm depth, whereas O-alkyl C and signals from lignin decreased (Dai *et al*., 2001). This indicated that the degree of SOC decomposition increased with depth.

The C-13 NMR spectra for humic acids indicate that aromatic C undergoes structural changes with depth resulting in higher proportions of mostly C-substituted aromatic structures and/or higher proportions of non-lignin-derived aromatic structures (Kögel-Knabner, 2000). With increasing soil depth at three forest sites, Kögel-Knabner *et al*. (1991) observed a degradation of lignin structural units in humic acids.

In a soil profile (0–45 cm) under continuous corn thermochemolysis using tetramethylammonium hydroxide (TMAH) indicated that lignin-derived syringyl units were preferentially degraded at depth (Chefetz *et al.*, 2000). Both the ^{13}C-NMR spectra and TMAH chromatograms indicated that plant components decrease with depth as a result of mineralization, decomposition, and repolymerization processes. In 30–50-cm depth of both a corn and a forest soil, Gregorich *et al.* (1996) observed relatively fewer long-chain C compounds, including fatty acids, lipids, and sterols compared to 0–5-cm depth using pyrolysis-field ionization mass spectrometry (Py-FIMS). The subsoil also contained fewer monomeric and dimeric lignins and alkyl-aromatics. In a Humic Folisol, contributions of alkyl C at 64–82-cm depth were twofold higher compared to the overlying horizons indicating higher contents of more resistant organic compounds like long-chain aliphatics (Fox *et al.*, 1994). In contrast, in a Histic Folisol, the contributions of alkyl C between 82 and 151-cm depth were lower than in the overlying horizons but total aromatic C was higher, suggesting probably increasing lignin content. In the mineral horizons in forest soil, the leaching and decomposition of lignin components with increasing depth was observed as revealed by NMR and Py-FIMS (Preston *et al.*, 1994). In Typic Haplorthods under forest, alkyl C increased to 60-cm depth while O-alkyl C decreased for bulk soils, humic acids, and humin (Ussiri and Johnson, 2003). It was hypothesized that carbohydrates were preferentially degraded at depth, whereas recalcitrant alkyl C (cutin, suberin, waxes) was selectively preserved but may also have been synthesized by microorganisms. Lignin decomposition in deeper soil horizons was probably slowed down as the aromatic C fraction increased with depth. In a mixed-conifer forest, soil litter decomposition from the surface to 40-cm depth was characterized by increases in aromatic C and plant-derived alkyl C without the buildup of humified alkyl C which generally occurs in other ecosystems (Gressel *et al.*, 1996). The B horizons (91–169 cm-depth) in Ferralsols showed higher intensities in the aromatic C region and lower proportions of alkyl C than the A horizons (0–33 cm depth) (Gonçalves *et al.*, 2003).

IV. POTENTIAL OF SUBSOIL ORGANIC CARBON SEQUESTRATION

The sequestration of SOC can be achieved by increasing C stocks through sustainable land use and recommended management practices, by improving the depth distribution of SOC, and by stabilizing SOC as recalcitrant C with long turnover time (Lal, 2004a,b; Post *et al.*, 2004). One strategy for

sequestration in subsoil horizons is to increase C inputs into the zones of the soil profile that have slower decomposition rates (Lal, 2004b; Post and Kwon, 2000; Table V). Based on estimates for the SOC pool between 1- and 3-m depth by Jobbágy and Jackson (2000) and the estimates for maximum rooting depths by Canadell *et al.* (1996), the subsoil below 1-m depth has probably the potential to store between 760 and 1520 Pg C. These estimates are, however, highly tentative as the database is very small and estimates were restricted to soil profiles with natural vegetation excluding, for example, agricultural soils with an altered vertical distribution of SOC. Since as much as 33% of global annual net primary production is solely used for the production of fine roots (Norby and Jackson, 2000), promoting the growth of the root biomass and management of the vertical root distribution is, therefore, one option. Another strategy to sequester SOC in subsoil horizons is to select plants and cultivars with a below-ground biomass that is higher in biochemical recalcitrant compounds. Recalcitrance results in the stabilization of SOC due to the inherent chemical structure of the biomolecule (Gleixner *et al.*, 2001). Chemical recalcitrance appears to be the only mechanism for protection of SOC for long periods of time while adsorption and aggregation of OM in the soil only slows down the decomposition processes (Krull *et al.*, 2003).

Management practices must be aimed to optimize CO_2 utilization in photosynthesis to increase in particular the below-ground productivity (Batjes, 1998). A concomitant high surface litter input may also result in high concentrations of dissolved organic carbon (DOC). The DOC transported with the percolating water has the potential to be sequestered on mineral surfaces in deeper soil layers (Baldock and Smernik, 2002; Telles *et al.*, 2003). The availability of adequate water levels and nutrient supply for root growth promotes the accumulation of sustainable OC levels in soils by high root residue production (Swift, 2001). Growing leguminous cover crops tends to preserve SOC due to residue inputs from root biomass (Gregorich *et al.*, 2001). To provide a permanent input of OM into deep soil layers, maintaining a vegetation cover with a deep root system is important (Sommer *et al.*, 2000). The introduction of relatively deeply rooted vegetation into shallow-rooted systems (e.g., shrubs into grassland or afforestation of croplands) might store C deep in soil (Gill and Burke, 2002; Jobbágy and Jackson, 2000). The relative below-ground translocation of assimilated C by pasture can reach up to 80%, but only 60% by trees (Kuzyakov and Domanski, 2000). Long rotation would favor C sequestration in tree stands (Liski *et al.*, 2001).

Manipulating the quality and quantity of subsoil OM inputs from roots is another option to sequester C (Fernandes *et al.*, 1997). This can be achieved by selection of plant species and cultivars (Batjes, 1998; Mann *et al.*, 2002). Raising the proportion of plants with higher root-to-shoot ratios (e.g., wheat

Table V
Potential of Carbon Sequestration in Subsoil Horizons

Level	Strategy	Effects	Examples	Knowledge gaps
Ecosystem	Increase in proportion of land-uses with higher subsoil C stocks		Shrublands have deeper SOC distribution than grasslands	Insufficient database for agricultural soils
			Grasslands have deeper SOC distribution than forests	
Plant/cultivar	Selecting plants/cultivar that raise the subsoil C stocks			Differences between plant species/cultivars
		Releasing more DOC during decomposition		DOC dynamics (i.e., DOC retention in the subsoil)
		Slower decomposing roots	Conifer roots decompose slower than roots from broadleaf species	Insufficient database root decomposition in agricultural soils
			Roots from broadleaf species decompose slower than roots from graminoid species	
		Higher root-to-shoot ratios	Wheat has a higher root-to-shoot ratio than corn	Insufficient database
		Deeper root systems	Shrublands have deeper rooting depths than grasslands	Insufficient database on plant root systems
			Woody plants are more deeply rooted than herbaceous species	Maximum rooting depth of most root profiles
			Fine-root mean age increases with depth	Effect of high variability of rooting depths among sites
		Higher relative contribution of thicker roots	Slower decay of roots > 5 mm diameter	Proportions of fine to coarse roots
			Roots > 2 mm diameter are older	Standard method to quantify root production and loss
				Definition of root size classes

(*continued*)

Table V (*continued*)

Level	Strategy	Effects	Examples	Knowledge gaps
		Higher contribution of recalcitrant root litter compounds	Lignin concentration negatively correlated with root decay rate	Definition and determination of root litter quality in terms of decomposability
				Standard method for the determination of lignin
			Root-derived suberin is a major contributor to SOM in forest soils and grasslands	Quantification of the lifespan of root-derived molecular structures
			Lignins, tannins and suberans have a high preservation potential	Quantification of the lifespan of root-derived molecular structures
		Higher rhizodeposition		Direct contribution of rhizodeposits to SOC on the field level
		Higher proportion of plants associated with ectomycorrhiza than associated with arbuscular mycorrhiza	Mycorrhizal status probably affects root decomposition	Mycorrhizal influence on belowground litter quality
			Ectomycorrhizal hyphae may be more recalcitrant than hyphae from arbuscular mycorrhiza	C sequestration by accumulation of mycorrhizal detritus
Soil fauna	Manipulating of soil fauna (i.e., the invertebrates)		C mineralization in earthworm casts is reduced—especially in the subsoil	Translocation and sequestration of carbon in the subsoil
		Directly by feeding with attractive food	Plant litter rich in Ca, N, moisture, carbohydrates attract invertebrates	Prediction of invertebrate effects on ecosystem-level fluxes of C
		Indirectly by providing favorable soil chemical and physical properties for faunal activity	Invertebrate feeding leads to an enrichment of recalcitrant SOM	

Soil microorganisms	Managing of soil microorganisms		Old and recalcitrant alkyl C originates partially from microorganisms	SOM quality and microbial communities in the subsoil
			Alkyl C increases in the subsoil	Contribution of microorganisms to alkyl C in relation to plants
		Promoting C release in the subsoil “primer plants” with deep, thick and fast decomposing roots providing channels for the establishment of subsoil microbial communities		Studies on subsoil C sequestration by soil microorganisms

instead of corn) will probably result in higher SOC stocks in deeper soil horizons. Selecting species and cultivars higher in lignin contents in the root biomass contribute also to C sequestration, although globally lower root Ca concentrations and higher C:N ratios have a stronger impact on slowing down root decomposition (Silver and Miya, 2001). Slower decay rates were observed for roots greater than 5 mm in diameter compared to fine and intermediate-diameter roots (2–5 mm), probably due to higher proportions of resistant organic substances in thicker roots. Plants/cultivars with higher relative contribution of thicker roots may, therefore, be suitable for fostering C sequestration. The long-term stability of biomacromolecules can be assessed from geological samples (De Leeuw and Largeau, 1993). During sedimentation and diagenesis, lignins, tannins, and suberans show the highest preservation potential. Selecting plants/cultivars with high contents of these compounds in the below-ground biomass may therefore promote SOC sequestration in soil profiles. New technologies may be used to modify chemical recalcitrant compounds in plants/cultivars for C sequestration (Chen *et al*., 2004; Pilate *et al*., 2002; Ralph *et al*., 1998). Plant/cultivars may also differ as a source for SOC accumulation in the subsoil by differences in rhizodeposition but the contribution of rhizodeposits to SOC has not yet been directly measured in the field (Allmaras *et al*., 2004).

The transfer of SOC to deeper soil layers and increase in SOM stability may also be promoted by manipulating the soil fauna (Wolters, 2000). Invertebrates like earthworms and many other taxa (e.g., ants, termites) transport OM and mineral soil by bioturbation. Potentially manageable soil fauna include earthworms and termites, which modify the soil environment through bioturbation (Fernandes *et al*., 1997; Lavelle and Spain, 2001). Reducing disturbance by adaptation of crop cultivation practices (e.g., reduced or no-tillage) and providing favorable soil chemical and physical properties indirectly promotes soil faunal activities (Mitchell and Nakas, 1986). Soil invertebrates exhibit different feeding preferences, and attractiveness of litter to many invertebrates is positively correlated with Ca, N, moisture and carbohydrate contents, and negatively with the polyphenol and tannin concentrations (Wolters, 2000). Selecting plants/cultivars with favorable litter qualities for invertebrates may, therefore, directly promote SOC stabilization and the horizontal transfer within the soil profile. However, knowledge gaps include the faunal food selection and associated changes in C pools as well as differential effects on SOM turnover (Wolters, 2000). For example, fungi are a primary food source for many invertebrates, including earthworms.

The largest fraction of OC entering the soil is that contributed by plant residues (Paul and Clark, 1996). Managing microorganisms that carry out the decomposition of plant litter in the subsoil may promote C sequestration

as the contribution of microbial products to SOC vs. plant inputs increase with soil depth (Martens *et al*., 2003; Rumpel *et al*., 2002). Microorganisms produce hydrolysis-resistant aliphatic biomacromolecules containing alkyl C (Hedges and Oades, 1997). These microbial-derived aliphatic materials may represent a relatively stable C pool and accumulate at depth (Golchin *et al*., 1996; Lichtfouse *et al*., 1995). An important fraction of the hyphal biomass in mycorrhizal tissues are recalcitrant compounds like chitin and glomalin that may account for a significant pool of SOM (Treseder and Allen, 2000). Ectomycorrhizal hyphae and exudates are probably more recalcitrant than arbuscular mycorrhizal ones (Langley and Hungate, 2003). Managing subsoil microorganisms to enhance C stabilization may be achieved by promoting C release from roots, retaining crop residues at the fields, reducing tillage, and feeding microbes (Post *et al*., 2004; Welbaum *et al*., 2004). However, the knowledge on soil microbial communities including mycorrhiza and their possible role in subsoil C sequestration is limited.

V. CONCLUSIONS

To date, studies on the potential for long-term C storage in soils have been restricted to the upper soil section mainly to the plow layer or up to 1-m depth. However, many soil profiles are deeper and the occurrence of roots at greater depths raises the question about the role of subsoil horizons to C storage. Furthermore, the mean residence time of SOC increases and the proportion of recalcitrant plant litter compounds tends to increase with depth. The paucity of available studies, however, hampers the knowledge of the potential for C sequestration in subsoil horizons. Subsoil SOC storage may be promoted by translocation of OM into deeper soil layers as DOC with the percolating water and due to bioturbation by soil animals. The most promising approach, however, may be to increase the contribution of the belowground biomass (i.e., roots, mycorrhiza, microorganisms). Plant roots contain higher amounts of chemical recalcitrant compounds (e.g., lignins, tannins, suberins) than shoots, and root-derived C accumulates with soil depth. Uncertainty exists if compounds like glomalin found in mycorrhizal tissues accumulate in the soil. The soil microorganisms may contribute highly aliphatic biopolymers to the SOC fraction in the subsoil that is protected for long periods of time.

Agricultural and forest land-use are mainly aimed at maximizing the above-ground growth. The focus must be to raise the proportion of chemical recalcitrant SOC, especially in the subsoil, as recalcitrant compounds in the subsoil have the highest potential for C sequestration. Studies are needed

to develop techniques for managing the above- and below-ground parts of ecosystems/land uses, including the plants with their above- and below-ground litter input, the soil fauna, and soil microorganisms for SOC sequestration.

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SOIL SCIENTISTS IN A CHANGING WORLD

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I. INTRODUCTION

Society is changing rapidly: Continuing economic growth and globalization, rapid technological developments, and a steady increase of the flow of information leads to often unpredictable and bewildering transformations (Castells, 2000). In our western democracies, such transformations contribute to a flexible, modern network society that does not match the more traditional and hierarchical relationships between government and its

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citizens that dominated earlier societies. Old principles of hierarchical democratic government are increasingly being challenged as alienated citizens feel that their interests are not well represented by their elected representatives, as evidenced by low voter turnouts during elections and the success of protest parties. Changes in society have, of course, always occurred in history. After the rather static agrarian economy before the nineteenth century, the industrial economy brought fundamental changes in the ninetieth and early twentieth century that were transformed again as the service economy developed after the 1970s. Now, in the West, there is increasing awareness of the "experience economy" as the impact of the media becomes ever more pervasive (Pine and Gilmore, 1999). Three reasons may be given to explain this latest development. The first is the material well-being in our western world, where the basic needs of life are met for many people and there is money to spare for luxury. The second is individualization, the unimpeded freedom to follow one's individual tastes and desires (Giddins, 1991). The third reason, globalization, appears contradictory at first sight with the second but does play a significant role. Processes and events all over the world have more and more in common, if only because of evermore effective global communication. Traditional institutions, such as the nation-state, become less important than cultural communities, which are networks from global to local scale, organized around particular values and interests. So far, this analysis focused on developed countries, but globalization is particularly relevant for developing countries as the gap between rich and poor in north and south widens rather than becomes smaller. The United Nations millennium goal, to reduce global poverty by 50% by 2015, illustrates an increasing awareness that global well-being cannot exist when 800 million people have to get by with less than one dollar a day.

Do these societal changes and global challenges affect science? And, more particularly, soil science? To answer that question it is important to avoid the trap of making an exclusive analysis from our own perspective rather than trying to really comprehend and integrate visions by others, be it colleague scientists, citizens, stakeholders, planners, or politicians. An inward-looking attitude does not create mutual understanding and all too often leads to a sterile debate. Better ways have to be explored. We need help here, and philosophy and sociology can offer valuable insights into the processes involved and their context. To come to grips with the challenge to realistically articulate different visions and approaches as to what is perceived to be the future role of science in society, Habermas (1984) distinguishes three basic human abilities to cope with the mysteries of life: (i) creating knowledge by using objective standards, (ii) having joint experiences of groups of people, as codified in social norms and values, and (iii) enjoying and cherishing individual experiences. This three-fold distinction, which has universal significance and applies to developed and developing

countries alike (be it in quite different ways), is helpful in articulating the relationships of scientists, individually and within a group, with their professional colleagues and with society at large. Such relationships are particularly important for soil science because it deals with land and its use. This has a particular appeal to humans as it visibly and directly affects their lives, even though city dwellers are farther removed from the earth than their rural brothers and sisters.

There are signals that relations between science and society are changing. Recently, for example, a new major government program on innovation research was initiated in The Netherlands to the tune of 800 million euros. These funds were *not* provided to universities or research institutes but to a consortia consisting of industrial firms, governmental and nongovernmental agencies, citizens groups, and, yes, scientists. Science institutions by themselves are no longer the logical and exclusive recipient of research funds. At the same time, state-funding levels of universities and research institutes are cut while being increasingly subject to deliverables in terms of specific output or of cost-sharing arrangements with industry.

Considering these diverse developments, the overall objective of this paper is to explore developments in soil science, considering the above-mentioned structural changes in society, by (i) analyzing the above-mentioned three basic human abilities in terms of their implications for the relationship between soil science and society, and (ii) considering the possible implications for soil science in future, emphasizing relationships with various stakeholders and policymakers.

II. TRUE, RIGHT, OR REAL?

A. Introduction

For a long time, philosophers (Fig. 1) have recognized and distinguished three basic human abilities to cope with the mysteries of life: (i) to think and to gain knowledge, (ii) to act in a group setting with common norms and values, and (iii) to feel and imagine. The Greek philosopher Plato was the first to make these distinctions in terms of, respectively, *the logos, the ethos, and the pathos.* Kant wondered how an image of the world could be obtained and in exploring this he analyzed "phenomena of knowing, acting and feeling." Hume (1968) in his "Treatise of Human Nature" distinguishes three corresponding elements: "of the understanding," "of the morals" and "of the passions." Habermas (1984) has perhaps most thoroughly analyzed these three elements when characterizing communication among people: (i) statements are "true" when they can be defined according to an



Figure 1 Plato, Kant, Hume and Habermas: four important philosophers that distinguished in their own way between the concepts of true, right, and real to characterize reality.

objective standard, (ii) statements are "right" when they agree with the established norms of groups of people, and (iii) statements are "real" when they correspond with personal, individual feelings. In short, the first statement corresponds with "It," the second with "We" and the third with "I" (Habermas 1984). Since this paper is written from the viewpoint of a soil scientist, the "I" corresponds first with the view of a particular soil scientist, where, obviously, distinctions have to be made among scientists operating within the various subdisciplines. But the "I" also relates to the way individual citizens feel about the soil and the land. The "We" corresponds to the way in which soil science and its expertise is reflected in rules and regulations in society but also, in a more general way, to the way in which "groups of people" feel about soil. The "It," finally, is the favorite and classic domain of the scientist, how to measure soil features and soil behavior with scientific methods that are quantitative and reproducible.

The broad sketch of developments in society, presented in the introduction, has clear and fascinating relations with the three basic abilities of man as discussed. By paying almost exclusive attention to the study of soil as such ("It"), soil scientists have largely left the development of rules and regulations on land ("We") to lawyers and others, while also the personal identification of citizens with soil and land in the experience society (*their* "I") has only incidentally been nurtured. In the past, this was no problem. Research was done in splendid isolation and scientists defined their objects of study. Research results were published and, perhaps but not necessarily, passed on to others to be applied or enjoyed either by colleague scientists or interested citizens. Research was an independent activity with separate funding. What happened with research results was not their concern. Only a few decades ago, each member of society occupied a particular niche with well defined functions in a relatively static society. This still holds true in many non-western societies but in our part of the world, many changes have occurred. Our network society is fundamentally different, with experiences becoming

more important and needing to be nurtured. Rules and regulations increasingly result from intensive interaction between government and its highly opinionated citizens. If researchers are not directly involved in that process, their independently generated and well intended scientific contributions tend to evaporate. In other words, there is justification to *first* explore relations between developments in society, as discussed broadly previously, and the three basic abilities of man to cope with reality and, *second,* to try to interpret the results of this analysis in terms of recommendations for future activities in soil science. I will therefore first explore whether it may help to make distinctions between a ''true,'' a ''right,'' and a ''real'' soil.

III. THE "TRUE" SOIL ("IT")

A. Introduction

The ''true'' soil has been the favorite domain of the soil scientist, using ever more sophisticated methods to measure soil characteristics and to characterize dynamic soil processes. This has greatly expanded our knowledge about soils and been a major contribution to society at large as this knowledge was applied in many products and services. There is, however, a distinction between the soil, as such, with its static and dynamic properties and the manner in which soil is being used in many ways by many people and the effects thereof. The soil, as such, is being addressed at our scientific conferences, usually in different divisions. Soil physicists interact with physicists, chemists with chemists, etc. Recent conference programs do not differ that much from programs twenty years ago: yet another liquid is added to yet another soil column. Only the technology to determine the fate of such liquids has become much more sophisticated. Of course, basic understanding of soil processes is crucial to move forward and to maintain and support soil science as a separate, viable science that can confidently interact with colleagues in other sciences. Sparks (2004) has made an eloquent and well documented plea for utilizing the fascinating potential of new equipment to characterize our soils, making sure that soil science keeps in touch with scientific developments elsewhere. However, funding agencies are increasingly reluctant to fund basic soil research as such and basic research will increasingly have to become part of *research chains*, also including applied research. This will be discussed in more detail later in this chapter.

Effects of land use are difficult to predict in the same quantitative and unique manner in which, for example, a CEC (Cation Exchange Capacity) can be predicted because conditions are so diverse. There is no single magic answer to any given land-use question because many stakeholders are

involved with widely varying interests. One way to move away from the linear research mode (a + b = c) is to define risks and uncertainties that are associated with not only actual land use, but also with possible land uses in the future, including indicating the limits of science. Here, the term "risk" represents uncertainty that can be quantified in terms of probability of occurrence. The perception of uncertainty and risk is a key element of modern society and Beck (1992) even speaks of our "risk society."

B. Risk and Uncertainty

Van Asselt (2000) distinguishes seven categories of uncertainty, of which only the first two can be quantified. The remaining are structural:

(i) ***Inaccurate measurement***. "We roughly know" and have no technical opportunity at this time to make better measurements. We may want to invest in new technology to allow more and better measurements if this appears possible in principle.
(ii) ***Lack of measurements***. "We could know" if only we would be willing to spend the money for measurements, using existing techniques.
(iii) ***Cannot be measured (yet) but is felt to be real***. "We know what we don't know." For soil science, we can think, for example, of elusive issues such as "soil quality" or "soil resilience."
(iv) ***Conflicting evidence***. "We do not know what we know." Different types of measurements of the same feature give different results. For soil science, we can think of chemical measurements based on different extraction techniques that yield different numbers. Often, an arbitrary selection is made here for one particular method but that does not solve the basic problem.
(v) ***Lack of knowledge which can potentially be gained in the future***. "We don't know what we don't know yet."
(vi) ***Lack of knowledge which is unlikely to be ever gained***. "We cannot know" and,
(vii) ***Experiences of uncertainty beyond knowledge***. "We will never know."

The structural uncertainties serve to illustrate the limitations of the "true" soil concept. Another important aspect dealing with "truth" was emphasized by Popper, perhaps the most important scientific philosopher of the twentieth century. He stresses that the absolute truth does not exist. Science makes progress by trial and error, by rejecting hypotheses and not by trying to confirm one favorite hypothesis that is supposed to represent "the truth." This constant rejection and formulation of new hypotheses, by so-called "falsification," ought to be the name of the game of science. "Truth," therefore, is time-bound, at least when science has a high vitality.

So, the conclusion is that the soil scientist should try to define the "true" soil as well as possible but should be modest and know his limits. Only part of the uncertainties can be characterized. Room should be left for things we don't know yet or things we will never know. I find this enlightening. I used to be quite critical about claims of organic farmers who experience "vibrations" of organic matter and illuminating signs of "wholeness" that cannot be quantified with our available measurement techniques. I am ready to acknowledge now that there is much under the sun which we do not understand. So be it. Fortunately, at the same time we do understand a lot and are privileged to be able to focus in our research on what we can handle. In addition, a scientist should be guided by Popper's example but, at the same time, should realize that his real-life customers are allergic to scientists who "are not sure." If, for example, a given result can be presented with a probability of 90%, it may be presented to planners and politicians as "the truth" even though a scientist knows there is a probability of 10% that things are different and that different hypotheses are likely to arise in future.

An example may serve to specifically illustrate this important point. Sonneveld and Bouma (2003a) studied the effects of different nitrogen fertilizer applications on groundwater quality in a major sandy soil type in The Netherlands (Fig. 2). They considered three types of prominent land use

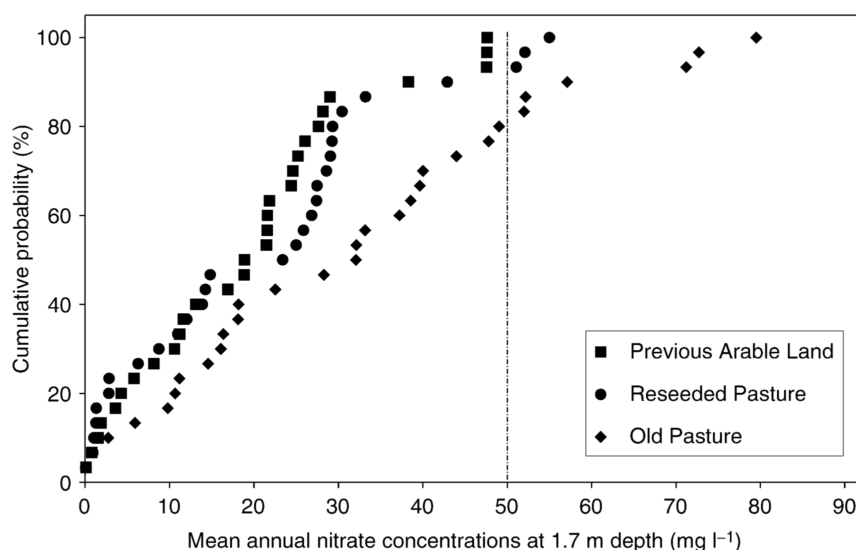


Figure 2 Cumulative probability of occurrence of the mean annual nitrate concentration at 1.7 m depth below surface in a major sandy soil type in The Netherlands at a common fertilization rate. Three land use types are distinguished as indicated. The EU quality standard is 50 mg/L (from Sonneveld and Bouma, 2003a).

in the area: permanent pasture (A), reseeded pasture (B), and land previously cropped to maize (C). They used a state-of-the-art simulation model for water and solute movement, Nitrogen dynamics, and plant growth, and made calculations for a 30-year period, using real weather and N-fertilization data that was similar for the three treatments. Results were expressed as probability graphs showing the probability that the quality threshold level for nitrate in the groundwater (50 mg/L) would be exceeded. Values were 25%, 8%, and 5% respectively for the three forms of land use, allowing the user to choose a level that he considers to be acceptable. Other scenarios could be explored with different fertilization rates offering more options. When asked for a clear-cut conclusion, we would say that permanent pasture presents unacceptable pollution risks at current fertilization rates, requiring development of different forms of management, whereas the other two land uses would present acceptable risks. But note that there always is a risk. For communication purposes, we set the degree of acceptability arbitrarily at 10%, but other limits can be defined, of course. Following this procedure, there are two ways two communicate: one clear statement to the user community and a hedged one to researchers. Of course, the availability of the probability data allows us to give background information to the users when asked, but only when asked.

C. The Pitfalls of the Precautionary Principle

When discussing the concept of the "true" soil, science faces an important principle that has been widely adopted in environmental sciences, the "precautionary principle." Adapted at the sustainability conference in Rio de Janeiro in 1992, the principle states: *"In order to protect the environment, the precautionary approach shall be widely applied by the States according to their capabilities. Where there are threats of irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."* The principle is often interpreted as "when in doubt, don't do it." This is wrong, if only because research is (or should be) always associated with doubt. An interpretation along these lines would, therefore, mean the kiss of death for research. But the principle implies, on the contrary, that lack of full scientific knowledge may not be a reason to do nothing, again emphasizing that trying to achieve absolute certainty is not realistic.

Use of probabilistic approaches, as discussed above, is helpful to define different options for land use from which rational choices can be made. Simulation models are essential tools to make such analyses possible because they involve "what-if" questions that cannot be answered by only looking at available information.

IV. THE "RIGHT" SOIL ("WE")

A. Introduction

How much is soil science part of our culture, our norms and values, our rules and regulations? The awareness of soil goes right back to the start of our civilization. In Genesis, the first book of the Christian bible, we read "God Yahweh formed man out of the soil of the earth . . . and man became a living soul." Also in other religions and cultures, soil and land play an important role (Hillel, 1991; Lines-Kelly, 2004). In our technological society, the role of the soil has moved into the background. Environmental concerns focus on global change and the status of tropical rainforests and the oceans, not primarily on the land. The problem of hunger in the world is not primarily seen as a result of the low productive capacity of soils but of poor distribution and marketing of the food that is grown along with the inability of the poor to buy food. The successful "green revolution" was an exclusive triumph of plant breeding without a clear role for soil science, and soil-related desertification and various other forms of land degradation are mostly seen as a result of poor management rather than as soil-related phenomena. Gilkes (2004) is critical of soil scientists because of their apparent inability to draw effective attention to the importance of soil and contribute to better soil management practices. On a more local scale, we see that environmental rules and regulations define critical contents of heavy metals and other pollutants in soils, thereby using soil data, but many other regulations tend to emphasize technical *means* rather than soil processes to define environmental *goals* for soil, air, and water quality. For example, the EU nitrate guideline of 1991 for groundwater defines the fertilization rate (170 kg N from organic manure) as the environmental threshold value in the law rather than the nitrate content of the groundwater itself which is, of course, the key quality parameter. Soil processes play a central role in determining the nitrate content of groundwater but have little impact on the fertilization rate. Moreover, soils are most often considered in a generic manner, thereby ignoring the possibility to be more specific about soil behavior using stratification of soils into different soil types (Sonneveld and Bouma, 2003b).

Soil scientists have a major handicap: soils occur underground and are invisible except when excavated. Plants and animals are highly visible, at least partly explaining the viability of policies enforcing biodiversity. The new environmental and farming policy of the European Union starting in 2007 emphasizes, among other matters, the importance of cultural heritage as expressed by characteristic landscapes. That soils have played an important role in creating such landscapes remains underexposed. Still, there are

efforts now to define soil-charters and the EU is working on soil policies. Recently, the Department of the Environment, Food and Rural Affairs in the UK published the "First Soil Action Plan for England" (Dept. EFRA, 2004). This needs support. But how can we contribute to the incorporation of soil expertise into laws and regulations that reflect the concerns of society? We will address this question by analyzing the policy process that underlies implementation of such rules.

B. The Policy Process

The relation between science and policy making used to be rather simple according to the old linear or hierarchical model: once a problem was identified, research was initiated and all or part of the results were later codified in rules and regulations by regulatory agencies. They were responsible for enforcement. This has led to many problems because stakeholders felt that their expertise remained unused and generic solutions to problems were difficult to implement without taking local conditions into account. One answer is interdisciplinary research where "hard" and "soft" sciences are combined and where participatory approaches are followed (Beck, 1992; Bouma, 2001a,b; Campbell, 1994, Funtowicz and Ravetz, 1993; Roling, 2001). It is important here to distinguish different functions in a policy cycle: (i) the *signaling* function, recognizing the existence of a new problem at an early stage, (ii) the *policy design* function, which, once a new problem has been recognized, explores a range of possible solutions considering trade-offs between economic, ecological, and social demands of various stakeholders when trying to define sustainable options, (iii) the *decision making* function, and (iv) the *implementation* function, where decisions are implemented (Bouma, 2003). Research has different functions in each of these categories, as will be discussed.

1. The Signaling Function

The *signaling* function is important as it deals with creating awareness. How are issues put on the policy agenda? An example is early publications about global climate change that have ultimately led to a world-wide research program and, finally, the approval of the Kyoto protocol in 2005. In the 1950s, environmental problems were not recognized because they had not been shown to exist in a convincing manner. Only after the book *Silent Spring* was written in 1962 by Rachel Carson and, later, the report of the Club of Rome in the early 1970s, did environmental issues enter the policy arena. For soils, there are many publications about erosion and degradation,

but so far these signals have not led to major coordinated action in the policy arena. The signaling process has hardly been effective here. This does not necessarily imply that research or communication have been inadequate, but can simply mean that other issues are considered to be more important for society at large. Social security and health care in the developed world and HIV and poverty in developing countries logically draw more attention than soil conservation despite its importance in the long run. This example illustrates the need to be quite critical in the *signaling* process; only issues that are considered to be of major importance for society at large will make it to the list of issues being considered. So we have to choose carefully and focus all attention on the most serious issues. Recently, for example, attention has been focused on soils as important sinks for carbon and signaling. This is likely to have an impact on global change policies and soil research. Four elements will be considered when discussing the *signaling* function: (i) the role of stakeholders, (ii) the importance of having adequate data, (iii) deriving key questions, and (iv) ways by which those key questions can be introduced into the policy process.

The input of stakeholders, when selecting future issues to be studied, is very important. Stakeholders are seen here as individuals or groups that have a "stake" in the problem at hand. When considering sustainable development, all of us are stakeholders, be it that the "stakes" are quite different and that some "stakes" are bigger than others. Here, I therefore consider stakeholders to represent individuals or groups that have a relatively large "stake" in the problems at hand. Opinions of stakeholders are very important and they should be solicited, however, we owe it to them that we realize limitations involved. For example, when asking farmers about manure management and associated environmental rules and regulations, they can provide important input, but there is crucial information that they cannot possibly possess. It is not fair to them to suggest otherwise. How nitrogen fertilizers are transformed in soil and how they leach to the groundwater can only be measured and modeled by scientists. What is needed here is joint fact-finding and engagement where stakeholders and scientists jointly shape the *signaling* process, each providing his or her particular input.

At least two aspects are important when dealing with *signaling*. The first is the process of *self-referencing*, the tendency of individuals or organizations to consider the environment from their own limited perspective, including blind spots that may happen to be particularly important to others. A second aspect is the character of the *communication process,* which is not simply transmission of messages involving sending and receiving, but always involves "construction" by the receiver. He or she will interpret messages received, in his/her own *self-referential* way, sometimes to the extent that the sender of the message may feel grossly misunderstood or, worse, insulted. Pointing out such basic problems of communication and creating awareness

in early phases of the *signaling* process, perhaps by role-playing games, can strongly increase its effectiveness in the end and should be part of this activity. Finally, we must realize that stakeholders sometimes have strategic reasons to not give their real opinions. Special techniques beyond simple questioning may be needed to unearth real motives. In this context, much attention has been paid recently to game-playing (Henrich *et al*., 2004).

Signaling requires data which are often not available because we are dealing with new, so far largely ignored phenomena. Hard data are essential, however, because without reliable data arbitrary speculation and ideologically motivated approaches may replace science as a governing principle and this all too often results in exchanges that evaporate or drift away and do not yield convincing results. Modern ICT and the internet offer new opportunities to mine data that may have been assembled originally for quite different purposes. Still, new data may have to be gathered. Scientists often make a mistake here by applying their most modern, sophisticated, and expensive techniques right away. Often, supporting basic data are not available and such efforts may not only represent overkill but will also reinforce the widespread feeling that researchers are really only interested in doing their own thing. It is better to use a step-by-step approach (Bouma, 1993) where one starts with a simple analysis, often based on tacit knowledge of the stakeholders and, if available, data from literature. This approach also addresses a common complaint of non-scientists: *How come that after more than a century of research, researchers tend to emphasize the need for more research rather than try to fist mine results that have already been obtained?* This first crack at the problem will yield some results but also obvious gaps in knowledge. These can next be filled up with application of simple, rapid, and relatively cheap measurements or modeling techniques. Sometimes, problems can be solved this way (Bouma, 1992). If not, more sophisticated techniques can be applied, etc. This approach, when coupled with a cost-benefit analysis, leads to the choice for the best research approach for the occasion and has the advantage to engage the stakeholders in the joint learning process right from the start. All too often, we see that stakeholders are involved only at the end of a project in the *implementation* phase, being asked to give a stamp of approval without having been part of the learning process. Many stakeholders are no longer willing to accept this. One last point is that interacting with stakeholders when *signaling* new challenges requires participants to "rise above" the raw data. Data only becomes meaningful when it is transformed into information, which is data with a meaning. Information becomes valuable when it is transformed into knowledge, which is internalized information. And knowledge is most effective in a societal context when it is applied with wisdom, which may be described as the ability to know when and how to ventilate which type of knowledge and, often at least as important, when to remain silent. We may refer to the chain

of "data to wisdom" in terms of a *knowledge chain*. Research can get stuck in data and information when technical aspects of data generation and storage dominate the research process. Ideally, the entire knowledge chain should be pursued in research and this can be quite helpful in realizing a successful *signaling* process.

The *signaling* process has to result in more than general statements as to what is perceived to be a problem and what might perhaps be done to overcome the problem. A focus is needed that appeals to those who have responsibilities for *preparation* and *implementation.* Quite basic: "What's in it for them?" It is impossible to formulate general rules in this context but it is important to keep in mind that what is important for research is not necessarily appealing to others. One arbitrary example may illustrate the challenges involved. A South African research project, executed in the context of the Ecoregional Methodology Project (ISNAR, 2004), was initiated because of a concern about irregular and declining maize yields in the African Highveld region, and associated highly fluctuating price levels that made farming difficult. A local Maize Board, a governmental agency, had a formal responsibility to stabilize prices but had no means to predict yields and was therefore ineffective. Also, farmers could not obtain crop insurance or bank loans because of the unpredictable yields. A dialogue between farmers, bankers, insurers, members of the Maize Board, and researchers defined the problem and led, after much discussion, to a plan to use computer simulation of crop yields and development of a "weather generator" to better predict future yields. Thus, the problem was not only *signaled* but also framed into a context that appeared sufficiently promising for all participants to move into the *design* phase and into funding of preparatory work. Research had a clear and essential input here. On the basis of their tacit knowledge, farmers and bankers could not handle the problem. Discussions, however, were crucial to derive a common problem perception and common goals. If researchers just would have presented their research proposal with a central role for modeling crop growth, the initiative would most probably not have materialized because initially farmers and bankers were quite critical.

As stated, the *signaling* process has to draw the attention of policy or decision makers. Framing of the problem is therefore very important. Showing the regional impact of certain problems and of measures to be taken, using modern GIS techniques, is one effective way to draw attention when dealing with land-use issues, a common activity for soil scientists. This works much better than presentation of abstract texts, tables, and figures that are not geo-referenced. An example, dealing with forest preservation and land-use change, will be given for the Philippines, using the CLUE model (Verburg and Veldkamp, 2004). Conditions in 1990 serve as a basis (Fig. 3a). Seven land-use types are presented for the entire country. Next, two scenario were explored; the first for 2010 (Fig. 3b), represents a baseline

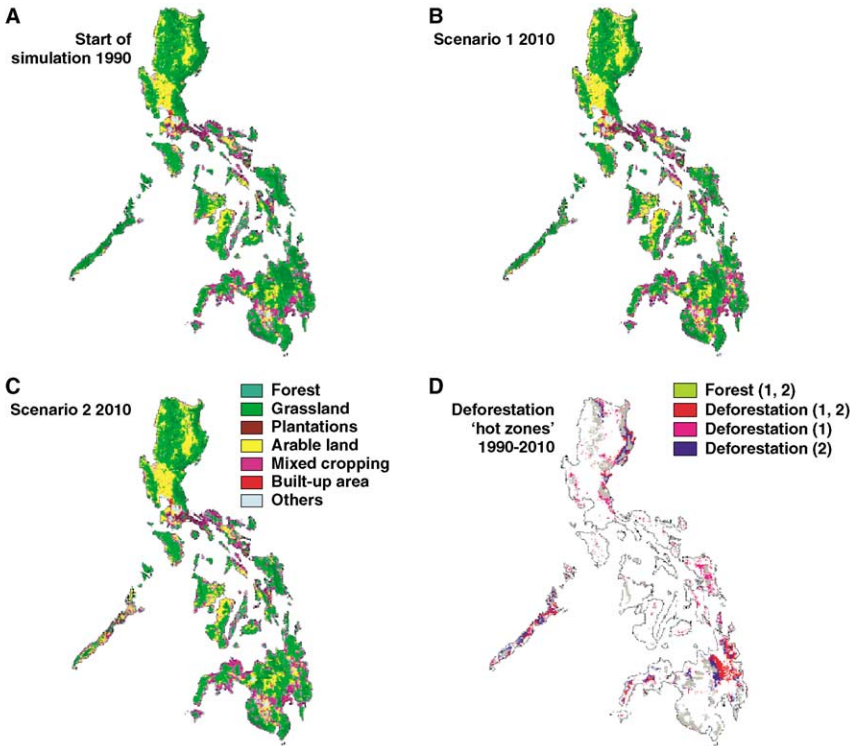


Figure 3 Results of land-use scenarios based on conditions in 1990 (A). Scenario B shows what might happen by 2010 if current drivers of land use do not change, while scenario C shows the effects of implementation of land-use policies. Map D shows where forest will occur in 2010 and which areas are likely to be deforested, creating "hot-spots" (from Verburg and Veldkamp, 2004).

scenario assuming that the drivers for land-use change of the last decades, as determined by CLUE, will remain in effect. One question arises: "What might happen if nothing changes?" The results, not surprisingly, indicate a decrease of forest as a result of agricultural expansion and urbanization. But effects are different in different areas. The second scenario for 2010 (Fig. 3c) is based on the assumption that spatial policies proposed to the Philippine government will be implemented. This, in fact, already covers *design,* to be discussed later, as the question is: "What might be the effects of our policies?" These policies imply that agriculture will only be allowed to expand in areas with suitable soils and that logging restrictions in a number of designated areas are strictly enforced. A different map results. Finally, Fig. 3d shows the deforestation "hot-spots" for both scenarios, areas where the forest will be under the highest pressure. Such "hot-spot" maps are

particularly effective to communicate to stakeholders and policymakers as they indicate "where" and "when" certain problems are likely to occur and where policy measures would be most effective. Spatial differentiation, using GIS, is a very powerful tool to focus the *signaling* process when dealing with land-use issues. Of course, spatial differentiation is the very essence of soil maps and their input into spatial models is therefore quite relevant.

2. The Design Function

Policy design requires a special approach by research. The key relation and dialogue here is the one between government and its citizens, *not* the one between science and society, even though scientists may want to believe so! The relation between government and its citizens is a troubled one in many countries. The well known Dutch sociologist van den Brink (2002) made a study of the attitude of Dutch citizens versus their government. In it, 35% of the respondents felt threatened by their government and were outright scared; 45% did not care and were clearly alienated; while 20% were involved but in a highly critical manner—they felt that they could do a much better job than the government. The least that can be said is that "the government" has a problem and needs a range of approaches to deal with its citizens! A generic plea for participatory approaches to deal with policy issues is therefore meaningless.

The key question is how science can fulfill a facilitating and mediating role by inserting the right knowledge at the right time into the overall learning and interaction process that goes on between government and its quite diverse citizenry when preparing or implementing new policies. Problems dealing with land use are very complex, involving many different stakeholders with always conflicting interests. These are not problems with single "magic" and linear solutions (a + b = c). Scientists are not used to this. Many are still attuned to the linear model. They may produce what they and their peers consider to be excellent papers that are, however, not used as they do not fit in the societal discourse. We used to feel that this represents "their" problem but, increasingly, it needs to be seen as "our" problem as well. Scientists involved in land-use questions need therefore to develop a basic understanding about interaction processes and communication techniques. But let us also realize that the importance of interaction with stakeholders can be over-emphasized. Some tacit knowledge of stakeholders is clear nonsense, even though one would probably not want to say so to not endanger the interaction process. In many cases, however, input by stakeholders is very valuable. Good examples are available now for regional land use where exploratory simulation techniques have been used to produce various land-use options that help to focus the interaction process between

government and its citizens. Soil science has made significant contributions in this wider context (Bouman *et al.*, 2000; Kropff *et al.*, 2001; Kuyvenhoven *et al.*, 1998). An example will be presented for the Kenyan Highlands, as developed by the Ecoregional Methodology Fund (ISNAR, 2004). Western Kenya has a very high population density of 1100 persons per square kilometer. Current average income is $0.95 a day; this population is part of the 800 million poor people in the world targeted by the millennium goals of the UN to be reduced by 50% by 2015. What are the possibilities for sustainable development? First, the current situation has been characterized using GIS. Five broad types of land use are distinguished (Fig. 4a). Note the presence of many subsistance farmers near Nairobi. Next, two broad scenarios are shown of many others that have been developed. The first is a baseline scenario for 2020 (Fig. 4b), assuming that current institutional conditions do not change significantly in the future, implying the occurrence of internal and external market barriers, poor infrastructure, underfinanced and understaffed public institutions. Thus, agriculture and markets are not developed while there remains an apparent lack of innovation partly due to many rules and regulations. Figure 4b—in analogy to Fig. 3b—addresses the question "What might happen in terms of land-use patterns (and associated sustainability parameters) if current institutional conditions do not significantly improve within the next few years?" Note that in this projection, only subsistance farmers are found near Nairobi. So far, the process followed is part of *signaling,* as discussed previously. Figure 4c presents one result of *design*: "What might happen in terms of land-use patterns if institutional conditions are improved in a manner that appears to be attainable?" Figure 4c demonstrates "what" might happen "where" and shows that patterns are characteristically different in different areas, partly because of different soil conditions. This is powerful input for a policymaker who always has allegiances to certain constituencies and obtains an idea this way as to what the award might be when he decides to stick his neck out by actively promoting certain policies proposed. A key point to be made here is that the database and the CLUE model allow many other scenarios to be derived; Fig. 4c only presents one example. Ideally, scientists, stakeholders, and policy-makers should work interactively behind the computer, playing with alternative scenarios until viable compromises materialize. There should be no restrictions! Even the craziest ideas should be checked through by investigating their economic, social, and environmental implications. It will become clear later whether a given scenario or option is realistic or not. Too many discussions are aborted prematurely because of lock-ins, sometimes because a scientist feels that a certain option is "impossible." This may be the wrong signal at the wrong time even though it may be quite true. But the guideline should be "everything is possible" at first, as this strengthens the crucial engagement process of all involved. So note that research does

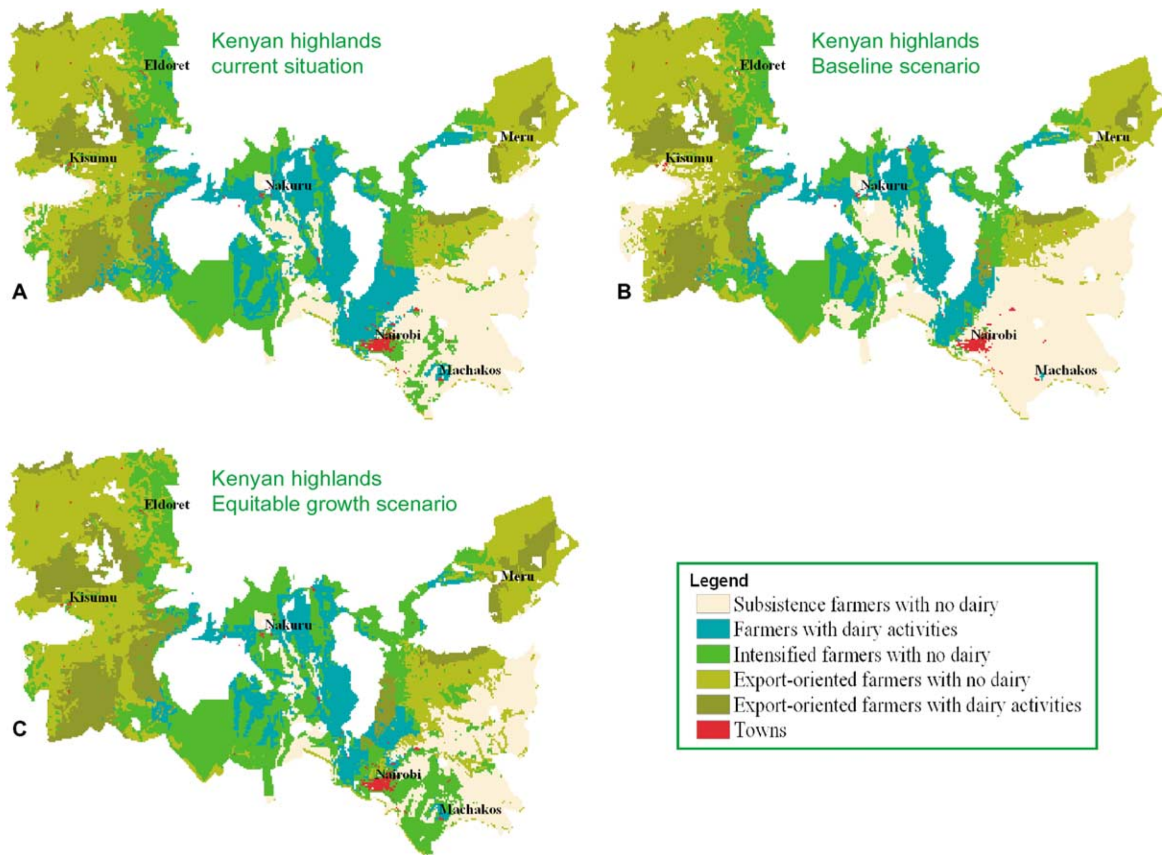


Figure 4 Land-use scenarios for the Kenyan Highlands, comparing current conditions (A), a baseline scenario for 2015 assuming no changes (B), and an equitable growth scenario (C). (derived from ISNAR, 2004 and corresponding website).

not define right away what should be achieved by 2020 and how it should be done! Research provides the indispensable tools to make a truly interactive approach possible, leading to "solutions" that represent an acceptable compromise to all stakeholders involved even though acceptance of the compromise is associated with grinding teeth all around as nobody has realized all his objectives. Engagement of stakeholders right from the start of *signaling* is, therefore, a key concept here. We should therefore no longer speak of *land use planning* but more of *land use negotiation.* Scientists can play a crucial role in this context as *facilitators* and *advisors* as they have a basic understanding of underlying processes. The challenge is to be acknowledged by all to be, in effect, the conductor of the process without standing up front in whitetails with a shining baton.

This may sound convincing but there have been many problems. An example is the manure policy in the European Union, as already briefly mentioned previously. In 1991, the nitrate guideline was adopted (EU, 1991), focusing on groundwater quality and allowing a maximum quantity of N from manure of only 170 kg N per hectare. This was applied for the entire European Union, ignoring different soils, land uses, and climates that have, of course, pronounced effects on nitrification and leaching processes of nitrates into the groundwater. Clearly, the *signaling* and *design* function had been ignored as the *decision* was simply announced. Farmers were unaware of these developments. Even worse, a political decision was made without much input by scientists, let alone soil scientists, a big mistake that has hounded the agricultural community ever since. After 1991, researchers in The Netherlands developed a new system based on a nutrient balance for individual farms, but this system was finally, after much struggle and debate, rejected by the European Court in 2003. Now we are back to the 170 kg organic N per hectare, which can approximately be translated into 1.8 animals per hectare. This generic rule is easy to enforce and is therefore attractive for regulators but has no direct relation to the pollution potential of manure. Nitrate pollution of groundwater is governed by soil processes but soils do not play a role in the legislation. Even more seriously, the innovative capacity of farmers as expressed, for example, by making better manure with less N or using split applications all the way to applying techniques of precision agriculture, is being suffocated as the generic rules are rigidly enforced. Not the *goal* of groundwater quality guides the regulations but possible *means* to reach that goal. Having failed in their *signaling* and *design* activities, soil scientists are now trying to devise a system where the water quality *goal* is central and where farmers are given the opportunity to reach these goals in their own way. In developing such a system, legal issues are by now much more important than soil or nutrient issues. Since 1991, thousands of scientific papers have been published about transformations of manure in soils, but they have ignored the political

context of the problem. The EU court action in 2003 illustrates the embarrassing effects of such an elitist attitude (Sonneveld and Bouma, 2003a; Sonneveld and Bouma 2003b).

3. The Decision Function

Going back to the policy cycle, *decisions* are made by politicians, by nongovernmental organizations, or by various entrepreneurs, not by researchers. Modern researchers should have *empathy,* the ability to put oneself in the position of somebody else, be it stakeholder or policymaker with the objective to better understand their motivations and aspirations (or devious plans, as it may be). They should, however, never go as far as complete identification. Scientists should not pretend to sit in the driver's seat that is reserved for stakeholders or politicians. Does that imply that scientists cannot have an opinion of their own and that they can only deliver sterile options from which others make a selection? Certainly not! They will often be asked what their personal opinion or recommendation is, and this can be given but always in terms of it being one option among many, including all tradeoffs involved.

4. The Implementation Function

Implementation of decisions again requires input by scientists, be it different input than before. Once decisions have been taken to select one of many options available, it is, however, not helpful when scientists come again with nice ideas as if the *signaling* or *design* process was still going on. To be effective, they have to follow the policy cycle all the way to effective implementation, which also involves evaluation. Too many projects have evaporated in the *design* stage with no decisions and, obviously, no valuable implementation in the end. Of course, mishaps occur, but too many failed projects are highly damaging for the research image.

What is the function of research in the context of *implementation?* It may be to better (again!) explain certain elements of the decisions made or to help solve unexpected complications or new developments. But it should all be done considering decisions being made and discussions being held during *signaling* and *design.* Moreover, scientists have a particular responsibility to emphasize that implementation has operational, tactical, and strategic dimensions, each with a characteristically different time frame. It is being said that policymakers often do not look beyond the short-term. But short-term operational measures may not satisfy longer-term strategic objectives. Being involved in the policymaking process and being recognized as a valuable partner makes it feasible for researchers to successfully stress

certain, more long-range interests that might otherwise disappear in everyday policy struggles. Here, science has a clear function.

V. THE CRUCIAL ROLE OF BASIC RESEARCH

A. Introduction

A diversified and interactive approach, implying that scientists are members of problem-solving teams, could imply a high content of, or perhaps even exclusive emphasis on, applied research. In fact, many scientists are concerned that embracing the stakeholders could mean that basic research is ignored, creating a major problem for science in the long-run. This concern has to be taken quite seriously. Basic research is essential to face the problems of the future. The widespread feeling in policy circles that "we know pretty much what there is to know after a hundred years of agronomic research and it is now more a matter of applying what we know rather than do more high-brow research" is, of course, not expressed in official policy papers but still significantly affects daily practice. So, how to ensure that basic research can continue? One way to tackle this problem is to follow a step-by-step approach, as discussed previously, to get the interaction process going by first introducing existing scientific knowledge and tacit knowledge into the policy process and by showing how this often leads to disappointing results that can be improved by new research (Bouma, 2002). This works better than introducing the new research right away. As we often work at different spatial scales, the process should be considered at different sequential levels in terms of "knowledge chains," connecting different types of knowledge at different spatial levels (Bouma, 1997). Again, there are different options for such sequential research at different spatial scales, each with a particular cost-to-benefit ratio.

Be that as it may, is it realistic to expect that soil by itself can be an effective driver to incorporate more science into the policy process? I fear this is not the case. Two aspects can be mentioned here: (i) broadening our case, where water scientists are our ideal partners, and (ii) looking for new applications and partners.

B. Interaction of Soil and Water

Water for soil is like blood for man (Bouma, 2005). Water regimes in soils and landscapes are determined by the climate, the vegetation, and by the particular properties of the soil and the underlying geologic formations and



Figure 5 Illustration of the "three-layer" concept in spatial planning in The Netherlands, considering first land *and* water patterns, then networks and infrastructure, and finally dwellings and settlements.

their hydraulic regimes. The recent proposal to emphasize hydropedology as a new discipline in which hydrologists work together with pedologists, both with knowledge about soils and landscapes in the field, deserves support (Lin *et al.*, 2004). Hydropedology can provide essential input into the policy debate that goes significantly beyond input by soil and hydrology separately; water regimes in different soils and landscapes determine agricultural and ecological potentials and their environmental behavior and resilience. The more we deviate from natural water and solute cycles, the higher the probability that the impact of man will negatively influence the sustainability of the land-use system.

This approach has de facto been adopted in Dutch spatial planning where the "three-layer" concept is being used. The first layer describes the dynamic soil and water system, the second the transportation networks such as roads and railways, and the third, human settlements (Fig. 5). Any new plan needs to consider the sequence from one to three when developing its content. Considering soil and geology and hydrology separately would not have been useful for this approach. But together, they form a solid basis for planning. This needs support and soil science needs to focus in this context on issues that are particularly important for defining solute fluxes in soils and landscapes.

C. New Applications

Traditional users of soil information may become less important while new users may offer new, attractive perspectives. They have to be actively pursued. But some traditional users may strongly change their demands as their own research focus changes. We cannot take our partners for granted in this dynamic period. An example is land-use studies. Statements in

published soil survey reports as to relative limitations of different forms of land use for any given soil become less relevant as more detailed data are needed in modern land-use models as discussed in Section IV. Use of soil data by traditional users should therefore not be taken for granted and their activities should also be actively followed. An example of new uses of soil information was described in Section IV for the South African Highlands by the Agricultural Research Service that started to cooperate with banks and insurance firms, showing that predictions of crop yields and associated risks were essential to improve financial policies. In these projects, soil scientists worked with agronomists and meteorologists (ISNAR, 2004).

Fitzpatrick (2004) demonstrated crucial contributions of soil science to forensic activities, a growing market. Using soil quality data for defining entire food chains is becoming increasingly important as critical consumers like to know where their food originates. Information and communication technology (ICT) plays a key role here by enabling *tracing and tracking* procedures, increasingly in the context of precision agriculture (McBratney *et al.*, 2005) . Also here, soil science will need to develop new ways to present its data. Existing databases are likely to not provide relevant data for new applications. Active exploration of the potential of soil science expertise is needed to help solve practical problems dealing with land use or food policy. This exploration should extend beyond our traditional clients.

VI. THE REAL SOIL ("I")

A. Introduction

How do we feel about soils? A distinction will be made here between individual experiences within the profession and experiences outside in society, by considering (i) the individual soil scientist, (ii) interacting soil scientists of different subdisciplines, (iii) soil scientists interacting with colleagues outside soil science, and (iv) citizens at large.

B. The Soil Scientist: From Data to Knowledge and Beyond

The future of soil science depends on research being based on genuine enthusiasm and curiosity of its scientists, which has to be safeguarded to a certain extent by allowing intellectual freedom allowed for by independent government financing. The biggest threat to the profession is a continued expansion of commercialization where activities tend to be restricted to short-term projects imposed by funding agents with narrow interests and

requirements which tend to stifle intellectual creativity. Every soil scientist will have his or her own inspiration, vision, and expectation for the profession. There should be room for that. Most researchers probably prefer to focus on the ‘‘true’’ soil. This is fine as long as others in future will also pay attention to the ‘‘right’’ and the ‘‘real’’ soil, getting involved in interdisciplinary and interactive processes, as discussed. If this does not happen, there is a bleak future for the profession. Our system of peer review should reflect the need for an approach that goes beyond counting the number of papers in refereed journals by also rewarding successful interdisciplinarity and interaction.

Dealing with soil questions involves a sequence of considerations, as discussed in terms of the *knowledge chain* in Section IV, starting with *data,* which becomes *information* when data obtains a certain meaning. *Information* becomes *knowledge* when it is internalized and when it becomes really part of one's own expertise. Effective application of *knowledge* requires *wisdom*, which cannot be extracted from literature and reflects an ability to judge whether or not certain knowledge should be applied in certain situations. *Wisdom*, however, can be cool and calculating. When dealing with people in defining the ‘‘right’’ and the ‘‘real’’ soil, *compassion* and *empathy* (the ability to see the world from the viewpoint of somebody else) are important qualities. I would recommend that we pay at least some attention to all these aspects in our education system and stop with looking at *data, information*, and *knowledge* in isolation. In the past, soil scientists were often more in contact with their users than they are now; pedologists, soil surveyors, and fertility experts talking to farmers and land users now find themselves often restricted to the office facing a computer screen. *Wisdom, compassion*, and *empathy* can only thrive through real interaction with real people. Here, we can be inspired by our professional experiences of the past.

C. Soil Scientists Amongst Themselves

The subcultures within soil science should work together more, without losing their identity. For example, for years pedologists have worked on Taxonomy, which was not very interesting for their colleagues in Soil Physics, Chemistry, Biology, etc. Now that Taxonomy is completed, there is good reason to join the activities of Hydropedology (Lin *et al.*, 2004) and consider solute fluxes in soils and landscapes as a unifying principle to which many other disciplinary activities in soil science can be attached and which can, together, yield a product that is attractive in a broader, interdisciplinary context. Another major challenge for soil science is the development of operational *soil quality* parameters. Many publications on soil quality have

appeared in the last decade, but we still do not have operational indicators that are comparable to those of water and air. This severely hampers the introduction of soil into environmental regulations and requires immediate attention. However, relatively simple expressions for *soil quality* are already to be found in soil survey interpretations in many countries that list *soil suitabilities* or *soil limitations* for a wide variety of soil uses. A low suitability implies a low quality, as do high limitations for a given use. This illustrates that different qualities have to be considered for any given soil depending on the type of use. This reasoning fits in the step-by-step approach, discussed earlier, where a plea was made to start simple to get the interaction and discussion process going.

Bouma and Hartemink (2002) analyzed developments in soil science in The Netherlands during the last 50 years and concluded that a first wave of supply-driven science was followed by a second wave of market driven science and that a third wave, reacting to post-modern developments in society, is still being explored. But scientists feel uneasy about this as their role quite strongly appears to change. Similar developments can be perceived in other countries. This paper intends to contribute toward establishing this third wave in everyday practice, also for soil science. One thing that is needed is cooperation among different soil scientists. The International Union of Soil Science has changed its purely disciplinary divisions into a mix of disciplinary and interdisciplinary divisions and commissions. This is to be applauded.

D. Soil Scientists and Their Colleagues

Within subdisciplines of soil science, there are generally good contacts with outside professions. In fact, those contacts are often stronger than those with colleague soil scientists. Soil chemists work with chemists, soil physicists with physicists, etc. Being an effective partner in an interdisciplinary team with economists, lawyers, political scientists, and sociologists—needed when pursuing sustainable development—requires much more. This was discussed in Section IV-B when dealing with the policy process. But we need to define better what our hardcore scientific competences are and which areas overlap with other disciplines. If those core competences are not perceived by others as being relevant and substantial, we—and any other discipline, for that matter—will have a problem trying to become appreciated members of interdisciplinary teams. This appreciation has to be earned, it does not come by itself.

There can also be a basic conflict between freely communicating our results and by still wanting to be involved ourselves. An example is *pedotransferfunctions,* which relate, usually by regression analysis, soil data to

parameters needed for simulation modeling (Bouma, 1989; Wosten *et al.*, 2001). For example, such functions relate texture, bulk density, and organic matter content to soil permeability and moisture retention properties. When engineers use these functions, soil scientists are not needed anymore, or so it might seem. Of course, they are still needed to put results in context, but this is not obvious to the general user. Besides, this is not a static matter as concepts are continually being developed further in any living science as is well demonstrated by McBratney *et al.* (2002). A similar story relates to soil mapping where off-the-shelf Geographic Information Systems offer smooth routines for non-soil scientists to transform point observations into patterns, but soil input significantly improves the quality of the work (McBratney *et al.*, 2003). If we do not continuously extend our own scientific frontiers, we should not be surprised when others do it in a way we usually do not like.

E. Citizens at Large

Land and soil strike a nerve in many people. Lines-Kelly (2004) sketched this eloquently for different cultures. We have not explored this to its potential, aside from an occasional popular article in newspapers and magazines or a TV documentary. Much more is possible. Our former soil survey reports used to describe geology and land use in detail, the latter often in a descriptive manner that was accessible to the average reader. Reports often included illustrated "walks" through the surveyed area. Current projects hardly allow time to report such a broader context. But there is more. The explosive development of the internet allows and requires new approaches. The great majority of households in developed countries are connected to the internet and the rest of the world will follow rapidly. Internet cafes can be found in the most remote areas of the globe. To tap and feed a genuine interest in soils, we could use the internet to present information on our major soils that not only describes their history in geological terms but also effects of use by man and, particularly, its potential for the future in view of expected economic developments and regulations. Such presentations go much beyond classical soil survey interpretations in terms of estimated limitations or suitabilities for various forms of land use and require computer simulations, of which some results were shown in Figs. 2, 3 and 4. Such a focus on the specific character of individual soils counteracts the often generic and demotivating treatment of soils in planning and legislation, "a soil is a soil is a soil." The real story is about the diverse properties of different soils, each with a unique potential where past land use can explain current properties of a given soil. Sonneveld *et al.* (2002) showed this for the soil organic matter content in a given sandy soil which could be well

predicted by regressing it with past land use. These predictions were based on visiting some 50 farms that had fields with the soil to be studied as derived from published soil surveys. New field work, including sampling soil organic matter and soil structure, was essential for this study to document changes being created as a result of different forms of soil management. Conversations with farmers and other land users yielded important tacit knowledge. Much unique soil data is still out there, waiting to be discovered. New techniques offer new possibilities to do so. The idea that field work is not necessary anymore, now that soil maps are completed, is truly mistaken and quite risky as it implies that we cut off our roots.

Much is yet to be gained by tapping and addressing the interest of our fellow citizens in soils in the context of the "experience economy." Alerted to the role of soils in modern land use, citizens can next more easily be mobilized when soil science is needed in the policy arena. We may think of establishing *communities of practice* (Wenger *et al.*, 2002) consisting of groups of people that share a concern, problem, or passion and wish to exchange and share their knowledge and experience to deepen their understanding as a basis for action. At least some soil scientists could join such *communities* as partners in learning. This idea is not new; existing examples of this approach are the Landcare Program in Australia (Campbell, 1994) and, on a much larger interdisciplinary scale, the activities of the International Panel on Climate Change (IPCC).

VII. WHERE TO GO FROM HERE?

The previous sections have suggested a need to move beyond the study of the "true" soil—which has received most emphasis in soil science in the past—and pay more attention to the "right" and the "real" soil. But these three categories have their own identities and relations between the three are not clear-cut. Besides, opinions on this are controversial. Many soil scientists find the type of discussion being presented here irrelevant, irritating, and a waste of time. How, then, to proceed? In view of the importance of the "experience economy," some of us may first want to start to further develop the concept of the "real" soil with particular attention to citizens at large, possibly by initiating *communities of practice* through the internet (Fig. 6). Here, selective input of "true" information by researchers is essential to fine-tune and sanitize what is perceived as "reality." Next, we have to see how we can better translate such perceptions of "reality" into rules and regulations about use of soil (the "right" soil) in the broadest sense. Again here, input of "true" soil information into interdisciplinary teams is essential. In other words, the key message would be that we need to feed our more traditional

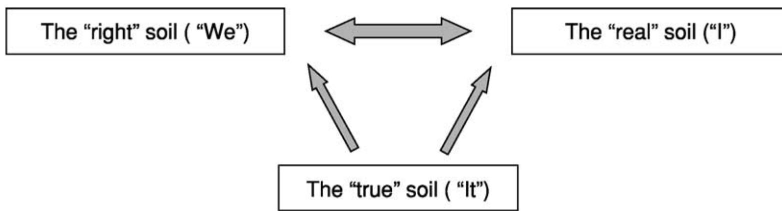


Figure 6 A proposed mechanism where individual experiences ("I") are related to societal arrangements ("We") while soil expertise, both applied and basic, ("It") is fed into this process to facilitate interaction.

soil research more effectively into research that characterizes the way soil is experienced by a wide variety of users, which, in turn is to be codified in written and unwritten rules and regulations guiding use of soil and land in society. This would appear to be the most promising sequence of activities for the future which certainly requires basic soil research, focused on the "true" soil. If we do not continually refresh our knowledge base with cutting edge soil research, we will find ourselves ineffective before long. Besides, we will be uninteresting as partners in interdisciplinary research teams with other scientists. Still, studying the "true" soil, as such, becomes increasingly difficult because of lack of funding. We have to demonstrate the absolute necessity of fundamental research to allow productive research on the "right" soil.

One final item needs to be mentioned. Aside from needing *Communities of Practice* we also need *Communities of Scientific Practice.* In other words, we have to get our own act together. We cannot afford anymore to see basic scientists ridicule their simple-minded applied colleagues or to see applied scientists publicly question the relevance of basic research. We should no longer consider communication as something that some specialist will hopefully do for us, funds permitting, or consider the role of being a facilitator in interdisciplinary teams as an academic dead end. We should not consider teaching to be inferior to research, because we have to realize new approaches in future by teaching and inspiring our students. In short, I would propose to establish *Communities of Scientific Practice* as "close-knit, interactive teams in which some scientists do fundamental, basic, strategic, or applied research in a chain-mode, while others cooperate in Communities of Practice or work on Communication and Education." This way we will be able to face our future in a strongly changing world as compared with a condition where we continue to play our separate, traditional roles. Bob Gilkes (2004) is right, as soil scientists we have failed in many areas, but rather than complain about the past we should now re-focus, mobilize our creative energy, and aim for the future.

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Enhancing Nitrogen Use Efficiency in Crop Plants

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Nitrogen is the most limiting nutrient for crop production in many of the world's agricultural areas and its efficient use is important for the economic sustainability of cropping systems. Furthermore, the dynamic nature of N and its propensity for loss from soil-plant systems creates a unique and challenging environment for its efficient management. Crop response to applied N and use efficiency are important criteria for evaluating crop N requirements for maximum economic yield. Recovery of N in crop plants is usually less than 50% worldwide. Low recovery of N in annual crop is associated with its loss by volatilization, leaching, surface runoff, denitrification, and plant canopy. Low recovery of N is not only responsible for higher cost of crop production, but also for environmental pollution. Hence,

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improving N use efficiency (NUE) is desirable to improve crop yields, reducing cost of production, and maintaining environmental quality. To improve N efficiency in agriculture, integrated N management strategies that take into consideration improved fertilizer along with soil and crop management practices are necessary. Including livestock production with cropping offers one of the best opportunities to improve NUE. Synchrony of N supply with crop demand is essential in order to ensure adequate quantity of uptake and utilization and optimum yield. This paper discusses N dynamics in soil-plant systems, and outlines management options for enhancing N use by annual crops.

I. INTRODUCTION

Nitrogen is element number 14 in the periodic table and was named "nitrogene" by a French scientist named Jean Claude Chaptal in 1790 (Smil, 2001). Essentiality of N for plant growth was established in 1872 by G. K. Rutherford, a Chemist from Scotland (Fageria *et al.*, 1997a). Near the end of the nineteenth century, Hellriegel and Wilfarth discovered that microbial communities could extract nonreactive N_2 from the atmosphere and convert it into a useable form known as biological nitrogen fixation (Galloway and Cowling, 2002). In relation to N, a significant breakthrough happened in 1913—the invention of a chemical process to convert atmospheric N_2 to NH_3 (Galloway and Cowling, 2002). Nitrogen deficiency is the most important nutritional disorder limiting crop yields worldwide. Hence, efficient use of N in crop production is crucial for increasing crop yield and quality, environmental safety, and economic considerations (Campbell *et al.*, 1995; Grant *et al.*, 2002). Total N inputs of the world's cropland is estimated to be about 169 Tg N yr^{-1} (Tg = Teragram = 10^{12} g) (Smil, 1999). This quantity corresponds to about 169 million metric tons of N. Out of this total N, 46% is added as inorganic fertilizers, 20% by biological N fixation from legumes and other N-fixing microorganisms, 12% by atmospheric deposition, 11% by animal manures, and 7% by crop residues (Cassman *et al.*, 2002).

Agricultural productivity gains since the 1950s resulted from the development of farming systems that relied heavily on external inputs of energy and chemicals to replace management and on-farm resources (Oberle, 1994; Porter *et al.*, 2003). High quantities of inorganic fertilizer, particularly N, have been used to increase world food production (Follett, 2001; Fageria *et al.*, 2003a). Nitrogen has long been recognized as a critical nutrient for productivity of annual crops (Miller, 1939). In tropical America, N deficiency

is a major soil constraint over 93% of the region occupied by acidic soils (Sanchez and Salinas, 1981). Nitrogen fertilizer, along with irrigation, dramatically increased food production in developing countries during the green revolution (1960 to 1980) (Follett, 2001). Furthermore, importance of N fertilization is proved by response of upland and lowland rice (*Oryza sativa* L.) (Fageria, 2001; Fageria and Baligar, 2001a), potato (*Solanum tuberosum* L.) (Hutchinson *et al.*, 2003), dry bean (*Phaseolus vulgaris* L.) (Fageria, 2002a), wheat (*Triticum aestivum* L.) (Fowler, 2003; López-Bellido *et al.*, 2003), maize (*Zea mays* L.) (Cerrato and Blackmer, 1990a), cassava (*Manihot esculenta* Crantz.) (Nguyen *et al.*, 2002), faba bean (*Vicia fab*. L.) (López-Bellido *et al.*, 2003), cotton (*Gossypium hirsutum* L.) (Chua *et al.*, 2003), sorghum (*Sorghum bicolor* L. Moench) and pearl millet (*Pennisetum glaucum* L. R. Br.) (Maman *et al.*, 1999; Pandey *et al*. 2001) to N fertilization reported in various regions of the world. A survey of nutrient use in the United States indicated that N fertilizer from commercial sources was applied to 97% of the area planted to maize (AREI Updates, 1996; Bausch and Diker, 2001). Furthermore, inorganic N fertilizers make up greater than 20% of the operating expenses in maize production in Canada (Tollenar, 1996), it is imperative that NUE be improved to increase net income for growers. Similarly, N is one of the most limiting nutrients for cereal production in many western African countries (Pandey *et al.*, 2001).

Soil is the principal source of N for most field crops and most of the crops obtain 50–80% of its N requirement from the soil even in cases where fertilizer N is applied at higher rates (Kundu and Ladha, 1995). However, chemical fertilizers are important complementary sources for maximum economic yield. The main reasons of N deficiency in crops are loss of N through leaching, volatilization, surface runoff, denitrification, and plant canopy. Furthermore, use of low rates for high yielding modern crop cultivars, especially by farmers in developing countries, is another reason for N deficiency (Fageria *et al.*, 2003a). In developing countries, intensive agricultural production systems have increased the use of N fertilizer in efforts to produce and sustain high crop yields (Fageria *et al*. 2003a). Consequently, N losses into the environment have also increased (Schmied *et al.*, 2000). Worldwide, N recovery efficiency for cereal production (rice, wheat, sorghum, millet, barley [*Hordeum vulgare* L.], corn, oat [*Avena sativa* L.], and rye [*Secale cereale* L.]) is approximately 33% (Raun and Johnson, 1999). Raun and Johnson (1999) estimated that the 67% of unaccounted for N represent a US$15.9 billion annual loss of N fertilizer.

Modern production agriculture requires efficient, sustainable, and environmentally sound management practices. Under these situations, increasing crop yields per unit area through use of appropriate N management practices has become an essential component of modern crop production

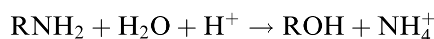
technology (Fageria and Barbosa Filho, 2001). Adoption of proper management strategies of N fertilizer may balance the supply of N required for optimum crop production while minimizing potential losses into the environment (Fageria *et al*., 2003a).

Mineral nutrition is one of the most important factors affecting plant productivity. N occupies a unique position among the essential plant nutrients for plant growth because of the large need of plants for N and its heavy losses in soil-plant systems. Under these situations, increasing NUE (nitrogen use efficiency) and decreasing N fertilizer rates can markedly contribute to conservation of air and water quality (Shoji *et al*., 2001). Efficient N fertilizer management can be defined as managing N fertilizer so crops use as much of the applied N as possible each year (Ferguson *et al*., 1994). The objective of this review is to discuss dynamics of N in soil-plant systems and appropriate management practices to improve N uptake and utilization by annual crops.

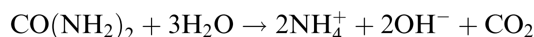
II. NITROGEN CYCLING IN SOIL-PLANT SYSTEMS

Information on N cycling in soil-plant systems is crucial to evaluate availability and loss balances of this nutrient to crop plants. According to Soil Science Society of America (1997), N cycling is the sequence of biochemical changes undergone by N wherein it is used by living organisms, transformed upon the death and decomposition of organisms, and converted ultimately to its original oxidation state. Looking into definition, N cycling in soil-plant systems is very dynamic and complex due to involvement of climatic, soil, and plant factors and their interactions. The addition, transformation, utilization, and possible losses of N from soil-plant systems are the main components of N cycling. The major part of N is added to soil through inorganic fertilizers. Other sources of N addition to soil are biological fixation, precipitation, gases adsorption, and organic manures (farmyard manures, green manures, and crop residues). The main transformations of N in soil-plant systems include fixation, mineralization (ammonification), nitrification, and immobilization. Mineralization is the conversion of organic forms of N to NO_3^- and NH_4^+ by microorganisms (Jansson and Persson, 1982; Stevenson, 1986). Since ammonia (NH_3) is the first mineral form produced, the process has also been called ammonification (Foth and Ellis, 1988). The NH_3 molecule is polar and readily combines with protons (H^+) to form ammonium (NH_4^+) (Foth and Ellis, 1988). Bolan and Hedley (2003) describe ammonification as enzymatically catalyzed microbial processes that hydrolyze organic and inorganic compounds to yield NH_4^+. The oxidation of NH_4^+ to NO_3^- is termed nitrification. If environmental conditions are not limiting, NH_4^+ is oxidized to NO_3^- almost as rapidly as it is formed (Schmidt,

1982). Thus, NO_3^- is usually the dominant form of plant available N in oxidized soils (Liang and MacKenzie, 1994; Kaboneka *et al*., 1997). Mineralization, ammonification, and nitrification can be expressed by the following equations:



$$RNH_2 + H_2O + H^+ \rightarrow ROH + NH_4^+$$

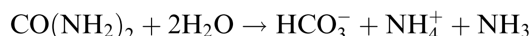


$$CO(NH_2)_2 + 3H_2O \rightarrow 2NH_4^+ + 2OH^- + CO_2$$



$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$

The ammonification process shows that urea hydrolysis results in consumption of H^+ or release of OH^-, whereas the nitrification process releases H^+. Hence, in the hydrolysis of urea, first pH around the urea granules may increase but when the process of nitrification is completed, $2H^+$ are released and soil pH decreases. However, Gaudin and Dupuy (1999) reported that urea hydrolysis generates alkalinity by the following reaction:



$$CO(NH_2)_2 + 2H_2O \rightarrow HCO_3^- + NH_4^+ + NH_3$$

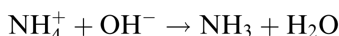
HCO_3^- is the dominant form of carbonate within the 6.4 to 10.3 pH range, and constitutes (together with NH_4^+) a slightly alkaline solution (Gaudin and Dupuy, 1999).

In addition to ammonification and nitrification in N cycles, denitrification and NH_3 volatilization are also important processes. Denitrification is defined as the microbial reduction of NO_3^- to N gases either as molecular N_2 or as an oxide (NO, N_2O) under anaerobic conditions (Bolan and Hedley, 2003). The denitrification process in agricultural soils is affected by NH_4^+-N and NO_3^--N concentrations (De Klein and Van Logtestijn, 1994), water content (Davidson, 1992), available C content (Rolston, 1981), and temperature (Mancino *et al*., 1988). Denitrification (emission of total N_2O, NO, and N_2) is higher under neutral and alkaline soil conditions compared with acidic conditions. According to Simek and Cooper (2002), this may be attributable to smaller amounts of organic C and mineral N available to the denitrifying bacterias under acidic conditions rather than a direct effect of low pH on denitrification bacterias. Denitrification is strongly correlated with soil moisture content (Aulakh *et al*., 1991; Mosier *et al*., 1986), and this process is higher under reduced soil conditions such as flooded rice culture (Fageria *et al*., 2003a). However, Porter *et al*. (1996) reported that denitrification can also occur in upland soils after a rainfall and the gaseous loss would be of short duration. Similarly, Porter *et al*. (1996) reported that in wheat-sorghum-fallow-wheat sequence, 10–13% of the applied fertilizer N that was unaccounted for was probably lost by denitrification or NH_3 volatilization.

Ammonia volatilization is defined as the conversion of NH_4^+ into NH_3 gas and that this gas is subject to loss. The process of NH_3 volatilization is more rapid in the alkaline growth medium compared to acidic medium. Denitrification and NH_3 volatilization can be expressed in the form of equations as follows:

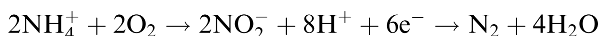


$$2NO_3^- + 2H^+ \rightarrow N_2 + 2.5O_2 + H_2O$$



$$NH_4^+ + OH^- \rightarrow NH_3 + H_2O$$

Denitrification can also take place under low O_2 supply, and high NH_4^+ concentrations with the equation written as follows (Bolan and Hedley, 2003):



$$2NH_4^+ + 2O_2 \rightarrow 2NO_2^- + 8H^+ + 6e^- \rightarrow N_2 + 4H_2O$$

The utilization of NH_4^+ and NO_3^- by plants and microorganisms constitutes assimilation and immobilization, respectively (Stevenson, 1982).

Absorption and loss of N through the plant canopy is also an important part of N cycling in soil-plant systems. Controlled as well as field studies showed that plants can absorb NH_3 from the air as well as lose NH_3 to the air by volatilization (Farquhar *et al.*, 1980; Hutchinson *et al.*, 1972; Stutte *et al.*, 1979). Emission of NH_3 has increased considerably over recent decades. Apsimon *et al.* (1987) reported a 50% increase in NH_3 emissions over Europe between 1950 and 1980, and concluded that this was mainly the consequence of intensive agricultural practices. Factors influencing NH_3 losses include soil and plant N status and plant growth stage (Sharpe and Harper, 1997). Abundant supply favors NH_3 losses, especially if the supply is in excess of plant requirements (Maheswari *et al.*, 1992). The loss of NH_3 through the plant canopy can occur during the whole growth cycle of a crop (Harper and Sharp, 1995; Morgan and Parton, 1989). However, some workers have reported that highest NH_3 volatilization rates for major agricultural crops occur during the reproductive growth stage (Francis *et al.*, 1997). Absorption of atmospheric NH_3 has been associated with low plant N content and with high atmospheric NH_3 concentrations (Harper and Sharp, 1995). A simplified version of N cycling in soil-plant systems is presented in Fig. 1.

Usually, 95% or more of the N in surface soils is present in an organic form, and the remainder is in mineral forms, including some fixed NH_4^+ (Legg and Meisinger, 1982). Organic matter has an average of 5% N (w/w); the plow layer of cultivated soils usually contains from 0.02 to 0.4% N (w/w) (Barber, 1995). These N percentage values will give about 400 to 8000 kg N ha^{-1}

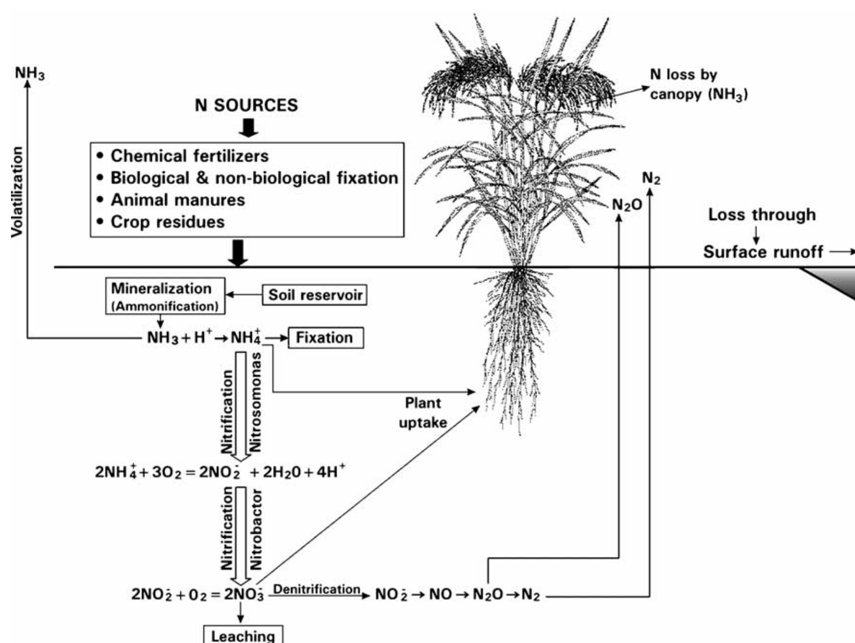


Figure 1 A simplified version of nitrogen cycle in soil-plant system.

in the 20 cm plow layer. Kundu and Ladha (1995) reported that the plow layer of almost 80% of rice-growing soils in Asia ranges from 2000 to 3000 kg N ha^{-1}. Foth and Ellis (1988) reported that many productive soils contain about 4000 kg N ha^{-1} in the plow layer and about 1% or less of the total N in soils is available to plants and microorganisms as NO_3^--N or exchangeable NH_4^+-N. Kundu and Ladha (1995) reported that at the International Rice Research Institute farm in the Philippines, the average N uptake by rice in the dry season was found to be 3.5–3.7% of the total N content in the 20 cm topsoil layer. However, the uptake of organic soil N depends on mineralization rate. These authors further reported that mineralization rate may vary from 3 to 8% of total N per crop season and about 50% of this mineralized N is supposed to be lost through various pathways. Tisdale *et al*. (1985) reported that in the temperate zone, the N mineralization rate was in the range of 1 to 4% during a crop growing season.

The main avenue of N loss from humid and sub-humid regions and irrigated agriculture is through leaching and denitrification. McNeal and Pratt (1978) reported that leaching losses commonly averaged 25–50% of the N applied in most cropping systems. However, Foth and Ellis (1988) reported use and loss of inorganic fertilizer N as 30–70% removed in the

harvested crop, 5–10% lost through leaching, 10–30% lost as gaseous compounds, and 10–40% incorporated into soil organic matter. These authors also reported that 50% of the fertilizer N was generally absorbed by the crop, 25% lost by denitrification, leaching, and volatilization, and 25% remained in the soil as mineral N or was incorporated into new organic matter. Nitrogen leaching loss may be determined by quantity of N applied, soil permeability, and quantity of rainfall or irrigation water. Higher N application rates and sandy soils normally have higher N leaching losses compared with adequate N rates and heavy textured soils (Davis *et al*., 2003).

Stevenson (1986) reported that the residual N in soil is relatively unavailable to plants during the second growing season and availability decreases even further in subsequent years because of conversion of N into stable humus forms. However, Bouldin (1986) reported that the N supplied by the soil is sufficient for rice yields of 2–4 Mg ha^{-1} in most situations. In Brazil, Fageria and Baligar (2001a) obtained about 3 Mg ha^{-1} of lowland rice yield in control plots (without N application) for three consecutive years. This indicates that soil N is an important source of N availability to annual crops in many cropping systems.

Nitrogen availability in submerged soils may be different compared with oxidized soils. In submerged soils (flooded rice), anaerobic respiration dominates, decomposition slows, and organic matter and nutrients accumulate in soil (Craft, 2001; Ponnamperuma, 1972). In contrast, upland soils usually are well drained, organic matter decomposes aerobically to CO_2 and, as a result, soil organic matter is low compared with wetland soils (Craft and Chiang, 2002; Schlesinger, 1997). Table I shows soil fertility of Brazilian oxidized Oxisols and lowland Inceptisols. Data in Table I show that on average lowlands (Varzea) have high organic matter and nutrients compared with upland soils (Cerrado).

In conclusion, added N in the soil is utilized by crop plants and also lost through leaching, denitrification, volatilization, and surface runoff. Nitrogen losses are also reported by plant canopies. Some N is also assimilated in the bodies of microorganisms and fixed on clay and organic matter. In this way, N cycling occurs in soil-plant systems.

III. FUNCTIONS AND DEFICIENCY SYMPTOMS

Since N is a major nutrient, it has many functions in the growth and development of crop plants. Nitrogen is a component of many important organic compounds ranging from proteins to nucleic acids. It is also a constituent of compounds like chlorophyll and alkaloids. Nitrogen improves root systems, which has special significance in absorption of water and

Table I
Selected Chemical Properties of Cerrado (oxidized) and Varzea (reduced) Soils of Brazil (0–20 cm depth)

Soil property	Cerrado (Oxisols)[1]	Varzea (Inceptisols)[2]
pH in H_2O	5.2	5.3
Ca ($cmol_c\ kg^{-1}$)	0.64	4.9
Mg ($cmol_c\ kg^{-1}$)	0.58	3.1
Al ($cmol_c\ kg^{-1}$)	0.64	1.3
P ($mg\ kg^{-1}$)	1.2	16.0
K ($mg\ kg^{-1}$)	47.2	92.0
Cu ($mg\ kg^{-1}$)	1.3	2.2
Zn ($mg\ kg^{-1}$)	1.0	2.4
Fe ($mg\ kg^{-1}$)	116	303
Mn ($mg\ kg^{-1}$)	14	59
OM ($g\ kg^{-1}$)	15	31
Base saturation (%)	17	50

[1]The data are average values of 200 soil samples collected from six states covering Cerrado region.
[2]The data are average values of 55 soil samples collected from eight states covering Varzea soils.
Source: Fageria and Stone, (1999).

nutrients under stress conditions (Fageria, 1992). Eghball *et al.* (1993) showed that N stress in maize reduced root branching. Similarly, Costa *et al.* (2002) reported overall greater root length and surface area with N fertilization compared to no N application treatment in maize genotypes. In addition, Kaspar *et al.* (1991) reported that maize root systems respond to zones of N fertility with increased root branching and greater number of small, higher-order roots in the fertilized soil layers. Several authors have shown that fertilizer N rate plays an important role in plant tolerance to corn rootworm (*Diabrotica barberi*) larval damage (Riedell *et al.*, 1996; Spike and Tollefson, 1988). These authors reported that if tolerance to rootworm larval-feeding damage is defined by the presence of a large root system and by the ability of the stem to stand erect, then banded N fertilizer placement can help improve tolerance to corn rootworm larval-feeding damage.

Yoshida (1972) reported that N functions to establish yield capacity and maintenance of photosynthetic activity during grain filling. Nutrient deficiency symptoms result from impaired metabolism within plant and decreased growth (Robson and Snowball, 1986). Nitrogen deficiency causes premature senescence and reduced yields (McConnell *et al.*, 1995). When plants do not receive sufficient amounts of a nutrient to satisfy their needs, they grow poorly and develop an abnormal appearance (Grundon, 1987). Deficiency symptoms on crop plants are typical for given nutrients; hence, it is possible to diagnose nutritional disorders by visual symptoms. Nitrogen

deficient plants show stunted growth, yellow leaves, reduced tillering in cereals, reduced pods in legumes, and consequently, yield reductions in both cereals and legumes. Nitrogen is a highly mobile nutrient in plants; hence its deficiency first occurs in the older leaves. Leaves become pale and yellowish-green in the early stages of growth, and become more yellow and even orange or red in later growth stages. Nitrogen deficiency enhanced senescence of older leaves. If deficiency persists for long durations, older leaves may dry and fall off in case of legumes. In cases of severe N deficiency, leaf area index and leaf area duration are reduced, which leads to lower radiation interception, lower radiation use efficiency, and lower photosynthetic rates (Barbieri *et al*., 2000; Fageria *et al*., 2003a; Muchow, 1988; Sinclair and Horie, 1989; Uhart and Andrade 1995). Nitrogen deficient plants produce mottled and low protein grains. Nitrogen is important in sucrose synthesis and in many reactions involving the utilization of sucrose as an energy source for plant growth and cell maintenance (Zinati *et al*., 2001). Nitrogen deficiency is generally expected in mineral soils with low organic matter contents, sandy soils which have been leached by heavy rainfall or irrigation, and intensive cropping with low rates of N application.

Nitrogen deficiency reduces vegetative and reproductive growth and induces premature senescence in cotton, thereby potentially reducing yields (Gerik *et al*., 1994; Tewolde and Fernandez, 1997). On the other hand, high N availability may shift the balance between vegetative and reproductive growth toward excessive vegetative development, thus delaying crop maturity and reducing lint yield (Howard *et al*., 2001). Early maturity (≈5 days) was also observed in lowland rice plots which did not receive N compared with plots receiving adequate N rates (Fageria and Baligar, 2001a).

IV. DEFINITIONS AND ESTIMATION OF NITROGEN USE EFFICIENCY IN PLANTS

The NUE can be defined as the maximum economic yield produced per unit of N applied, absorbed, or utilized by the plant to produce grain and straw. However, nutrient use efficiency has been defined in several ways in the literature, although most of them denote the ability of a system to convert inputs into outputs. Definitions of nutrient use efficiencies have been grouped or classified as agronomic efficiency, physiological efficiency, agro-physiological efficiency, apparent recovery efficiency, and utilization efficiency (Fageria and Baligar, 2001a, 2003a; Santos *et al*., 2003). The determination of NUE in crop plants is an important approach to evaluate the fate of applied chemical fertilizers and their role in improving crop yields.

The NUE are calculated by using the following formulas (Fageria and Baligar, 2003b; Fageria *et al*., 2003a):

Agronomic efficiency (AE) = $(G_f - G_u/N_a)$ = kg kg^{-1}

Where G_f is the grain yield of the fertilized plot (kg), G_u is the grain yield in the unfertilized plot (kg), and N_a is the quantity of nutrient applied (kg).

Physiological efficiency (PE) = $(Y_f - Y_u/N_f - N_u)$ = kg kg^{-1}

Where Y_f is the total biological yield (grain plus straw) of the fertilized plot (kg), Y_u is the total biological yield in the unfertilized plot (kg), N_f is the nutrient accumulation in the fertilized plot in grain and straw (kg), and N_u is the nutrient accumulation in the unfertilized plot in grain and straw (kg).

Agrophysiological efficiency (APE) = $(G_f - G_u/N_f - N_u)$ = kg kg^{-1}

Where G_f is the grain yield in the fertilized plot (kg), G_u is the grain yield in the unfertilized plot (kg), N_f is the nutrient accumulation by straw and grain in the fertilized plot (kg), and N_u is the nutrient accumulation by straw and grains in the unfertilized plot (kg).

Apparent recovery efficiency (ARE) = $(N_f - N_u/N_a) \times 100$ = %

Where N_f is the nutrient accumulation by the total biological yield (straw plus grain) in the fertilized plot (kg), N_u is the nutrient accumulation by the total biological yield (straw plus grain) in the unfertilized plot (kg), and N_a is the quantity of nutrient applied (kg).

Utilization efficiency (UE) = PE $\times$ ARE = kg kg^{-1}

The above mentioned five NUE for lowland rice were calculated and are presented in Table II. On average, all NUE were higher at lower N rates and decreased at higher N rates. This indicated that rice plants were unable to absorb N when applied in excess because their absorption mechanisms might have been saturated. Under these conditions, the possibility exists for more N being subject to loss by NH_3 volatilization, leaching, and denitrification. It has also been reported by Jarrell and Beverly (1981) that in any experiment with nutritional variable, plants grown at the lowest nutrient concentrations will inevitably have the highest utilization quotient because of dilution effects.

Decreasing NUE at higher N rates indicated that rice plants could not absorb or utilize N at higher rates or N loss exceeded the rate of plant uptake. Decreases in N uptake efficiency at higher N rates has been reported by Kurtz *et al.* (1984) and Pierce and Rice (1988). Similarly, Limon-Ortega *et al.* (2000) reported that NUE in wheat decreased as N rate increased. Similarly, Eagle *et al.* (2000) reported that NUE in rice, which has both

Table II
Nitrogen Use Efficiencies as Affected by N Fertilizer

N rate kg ha^{-1}	Agronomic efficiency Δ kg grain kg^{-1} N added	Physiological efficienty Δ kg grain + straw Δ kg^{-1} uptake	Agrophysiological efficiency Δ kg grain Δ kg^{-1} N uptake	Apparent recovery efficiency %	Utilization efficiency Δ kg grain + straw kg^{-1} N added
30	35	156	72	49	76
60	32	166	73	50	83
90	22	182	75	37	67
120	22	132	66	38	50
150	18	146	57	34	50
180	16	126	51	33	42
210	13	113	46	32	36
Average	23	146	63	39	58
R^2	0.93**	0.62*	0.87**	0.82**	0.90**

*,**Significant at the 0.05 and 0.01 probability levels, respectively.
Source: Fageria and Baligar (2001a); Fageria *et al.* (2003a); and Fageria and Baligar (2003b).

physiological and soil N supply components, decreased with increases in soil N supply, indicating that some of the decrease in NUE may have been due to the increased soil N supply. Maman *et al.* (1999) reported that applied N decreased NUE of pearl millet grain.

The ARE for flooded rice grown in Asia has been reported as ranging from 20 to 40% of applied N (De Datta *et al.*, 1987; 1988; Schnier *et al.*, 1990). These values were estimated using ^{15}N labeled fertilizer and by differences in methods for determining ARE values as calculated by Cassman *et al.* (1993). In some of these same studies, values ranged from 34 to 64%. Hussain *et al.* (2000) reported that ARE in lowland rice grown in the Philippines was 36%. Hussain *et al.* (2000) also reported that AE of lowland rice in the Philippines was 18 kg grain produced with the application of 1.0 kg N. Bronson *et al.* (2000) reported that ARE in transplanted rice grown in Asia was higher (54%) when the difference method to calculate values was used rather than when the isotopic dilution method (44%) was used to calculate values.

Even though AE and ARE of N have been reported in the literature for various crops, other efficiencies (PE, APE, and UE) have been rarely reported. The ARE in corn and sorghum has been reported to be about 25% from long-term plot research in Nebraska (Olson *et al.*, 1986) and 40% for wheat in Oklahoma (Raun and Johnson, 1995). For cotton grown in Texas, ARE has been reported to be in the range of 19–38% (Chua *et al.*, 2003) depending on management practices adopted. Randall *et al.* (2003)

reported apparent ARE for corn ranged from 31% for total applied N at preplant to 44% for the split treatment (total 150 kg N ha^{-1}, 40% applied as preplant and 60% sidedress at V8 stage as defined by Ritchie and Hanway (1984).

Halvorson *et al.* (2002) reported fertilizer N recovery by onion (*Allium cepa* L.) to be 15% and unfertilized corn recovered 24% of fertilizer applied to onion. Brown *et al.* (1988) reported ARE by onion to be 19–26% depending on rate and method of application. Huggins *et al.* (2001) reported ARE of corn to be 44% when grown in monoculture and 50% when corn was grown in rotation with soybean (*Glycine max* L. Merr.).

Cassman *et al.* (2002) reported that ARE in continuous lowland rice production systems in Asia to be about 31% and somewhat higher efficiency of 37% for corn in the major maize-producing states of the United States. Errebhi *et al.* (1998) reported that during high rainfall and leaching events, an average of only 33% of the applied N was recovered by potato. In the second year, when growing season was characterized by less total rainfall and fewer leaching events, ARE was 56%.

The ARE of fertilizer N by cotton plants has been reported to be low in field experiments (Stevens *et al.*, 1996). Yasin (1991) reported that ARE of cotton receiving 50, 100, and 150 kg N ha^{-1} was 34, 38, and 25%, respectively. Similarly, Stevens *et al.* (1996) reported ARE by cotton was 38, 28, 19, and 9% at rates of 45, 90, 135, and 180 kg N ha^{-1}. Constable and Rochester (1988) reported ARE of 30% for irrigated cotton grown on Vertisols. Wienhold *et al.* (1995) reported that corn grain utilized 35% and stored an additional 15% of the applied N fertilizer, while 30% of the N remained in the upper 0.6 m of the soil profile at the end of the growing season.

V. DRY MATTER PRODUCTION AND PARTITIONING

Information on dry matter production and partitioning between various plant parts is important in the development of crop growth models (Sheng and Hunt, 1991). In addition, the value of the agricultural experiments could be enhanced significantly if information on dry matter production and its partitioning are available (Royo and Blanco, 1999). This information should permit better analysis and interpretation of the results and also allow one a better understanding of processes and resource exploitation for crop production (Williams *et al.*, 1996).

Dry matter yield is an important plant component for determining grain yield in field crops. The plant ideotype (Donald, 1962, 1968; Doland and Hamblin, 1976) or plant architectural (Smith, 1976) approach to plant breeding has been primarily based on the concept of maximizing grain yield

per unit of dry matter produced (Sharma and Smith, 1986). Photosynthetic products produced by green plants are divided into roots, shoots, and grain. A part remains in shoots and a part is translocated to roots and grain. This process can be referred to as dry matter partitioning in plants. However, root weight is generally not taken into account when discussing dry matter partitioning and photosynthetic products divided into shoots and grain. Root weight contributes about 8–12% of total crop weight at harvest (Gallagher and Biscoe, 1978).

Dry matter production in rice has been reported to be significantly related to intercept photosynthetically active radiation (IPAR) (Kiniry *et al*., 2001). The rate of conversion of intercepted light into biomass is known as radiation use efficiency (Kiniry *et al*., 2001). Crop growth rate depends on the amount of radiation intercepted by the crop and on the efficiency of conversion of intercepted radiation into dry matter (Sinclair and Horie, 1989). Low N concentrations in plant leaves have been described as a factor for reducing RUE and biomass productivity (Sinclair and Horie, 1989). Sinclair and Horie (1989) and Muchow and Sinclair (1994) showed curvilinear increases in RUE with aerial leaf N contents. Radiation use efficiency (RUE) in modern crop cultivars has been high due to favorable plant canopy and consequently higher dry matter and grain yields. Hence, N requirements of modern crop cultivars are generally higher compared with old traditional cultivars. Variation in dry matter yield in response to N may arise from differences in the amount of intercepted photosynthetically active radiation by the canopy, the RUE, and grain harvest index (Charles-Edwards, 1982). Plants that are deficient in N will have lower photosynthetic rates and as a result, will generally accumulate less dry matter and produce lower yields (Dwyer *et al*., 1995; Sinclair and Horie, 1989).

Shoot dry matter accumulation of corn, upland rice, soybean, and dry bean during crop growth cycle is presented in Fig. 2. Dry weight of shoots of corn, upland rice, soybean, and common bean were significantly ($P<0.01$) influenced with advanced age of crop plants. Dry matter production of corn increased up to 84 days after sowing and then decreased. In upland rice, increases in shoot dry weight were up to 102 days after sowing and then decreased. In soybean, dry matter increases were up to 120 days after sowing and then decreased. Similar results were noted for dry bean dry matter increases up to 84 days after sowing and then decreased. The increase in dry matter with advanced plant age up to certain stages in four crop plants was due to increases in leaves, tillers in rice, branches in legumes, and culm weights (cereals and legumes). The decreases in dry weight after certain growth stage in four crops were associated with translocation of photosynthetic products to grain. In legumes, decreases in shoot dry weight were also associated with senescence of mature leaves. Shoot dry weights were higher in cereals (corn and rice) compared with legumes (soybean and dry bean)

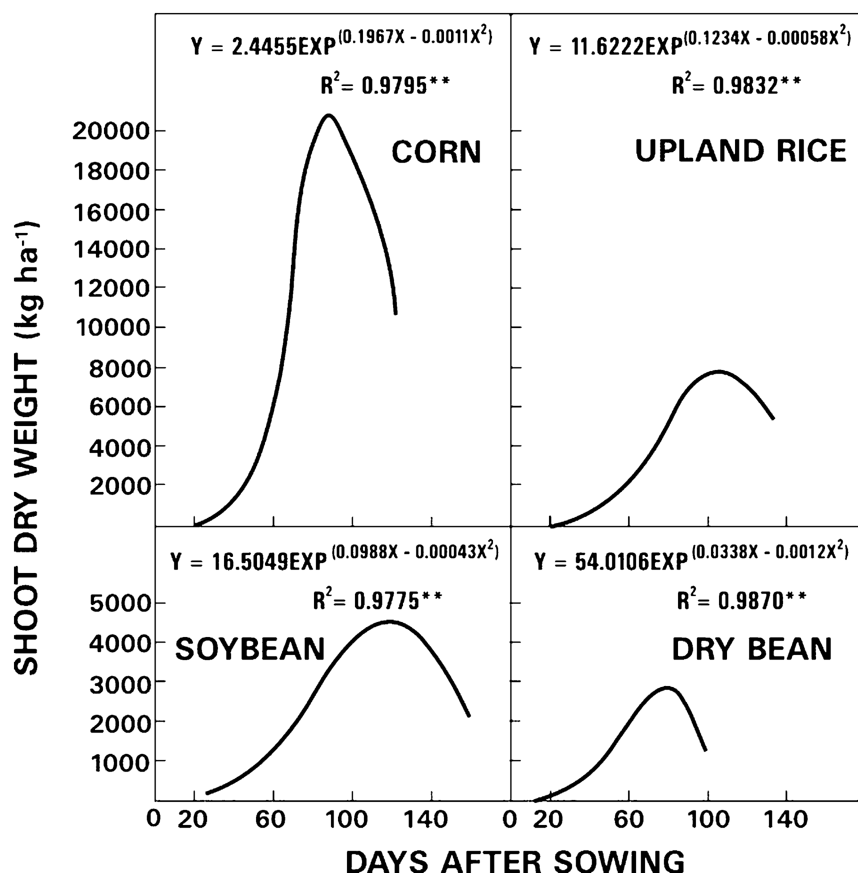


Figure 2 Shoot dry weight of corn, upland rice, soybean, and dry bean as a function of plant age. Adapted from Fageria (2004).

during all growth stages. The lower shoot dry weights in legumes were associated with higher photorespiration in legumes compared with cereals (Shinano *et al.*, 1991, 1993). Further, dry matter production efficiency per unit N absorbed was reported to be lower in legumes than in cereals (Osaki *et al.*, 1992). Figure 3 shows relationships between dry matter and grain yields of dry bean. Based on data presented in Fig. 3, it can be concluded that increasing dry matter increases grain yield in a quadratic manner.

López-Bellido *et al.* (2003) reported that high biomass is a prerequisite for achieving high faba bean seed yields. Loss and Siddique (1997), Thomson *et al.* (1997), and Mwanamwenge *et al.* (1998) also reported that seed yields of faba bean were positively correlated with total dry matter production at

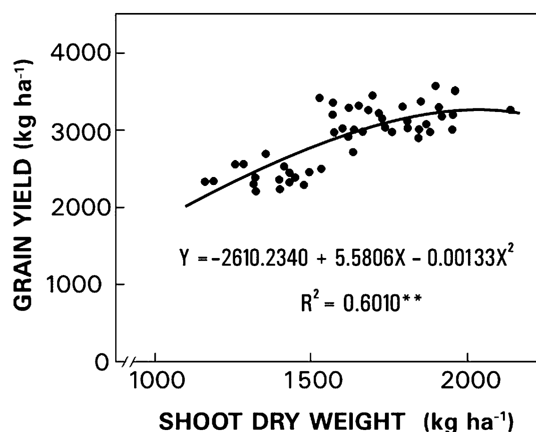


Figure 3 Relationship between shoot dry weight and grain yield of dry bean (Fageria *et al.*, 2004a).

harvest. Linear relationships between biomass and seed yields were reported for soybeans grown in Puerto Rico (Ramirez-Oliveras *et al.*, 1997) and Australia (Mayers *et al.*, 1991). Similarly, Board *et al.* (1996) and Rao *et al.* (2002) also reported strong positive correlations between yields and top dry matter in soybeans grown in the United States. Dry matter production had highly significant associations with grain yields of plants grown under relatively high heat environments (Reynolds *et al.*, 1994).

Grain growth is supported by photosynthetic activities of flag leaves and inflorescences, and also by translocation of stored photosynthetic product reserves in the plant canopy (Blum, 1988). It has been reported that dry matter accumulation in cereals prior to anthesis is an important source of photosynthetic products for grain growth, which is especially true for plants grown under hot and dry climatic conditions during grain filling (Papakosta and Gagianas, 1991; Shepherd *et al.*, 1987). Hence, it can be concluded that grain yields greatly depend on translocation of pre-anthesis assimilates to the grain (Royo *et al.*, 1999). Stem carbohydrate reserves have been estimated to contribute from 10 to 12% of the final grain weight in wheat grown under normal climatic conditions and more than 40% for plants grown under drought or heat stress conditions (Austin *et al.*, 1980; Rawson and Evans, 1971; Wardlaw and Porter, 1967). Similarly, Royo *et al.* (1999) reported that the contribution of pre-anthesis assimilates to grain yield was 46% in spring triticale (*Triticale hexaploide* Lart.) genotypes and 65% in winter genotypes, as the later maturity winter triticale genotypes were more affected by abiotic stresses.

A. Grain Harvest Index

Grain harvest index (GHI) is the ratio of grain yield to total biological yield. The term GHI was introduced by Donald (1962), and since has been considered to be an important trait for yield improvement in field crops. Doland and Hamblin (1976) discussed relationships between harvest index and yield, and concluded that this was an important index for improving crop yields. Thomson *et al.* (1997) reported greater seed yields of faba bean with higher GHI. Morrison *et al.* (1999) examined physiological differences associated with seed yield increases of soybean in Canada within groups of cultivars released from 1934 to 1992. These authors concluded that the increase in seed yield with year of release was significantly correlated with increases in GHI (0.5% per year), photosynthesis, and stomatal conductance, and decreases in leaf area index. They further concluded that today's cultivars are more efficient at producing and allocating carbon resources to seeds than were their predecessors.

This index is calculated with the help of equation: GHI = (grain yield/ grain + straw yield). Values for grain harvest index in cereals and legumes are normally less than 1. Although GHI is a ratio, it sometimes is also expressed in percentages. Generally, dry matter have positive associations with grain yield (Rao *et al.*, 2002), and N is important for improving GHI. Snyder and Carlson (1984) reviewed GHI for selected annual crops and noted variations from 0.40 to 0.47 for wheat, 0.23 to 0.50 for rice, 0.20 to 0.47 for bunch type peanut (*Arachis hypogaea* L.), and 0.39 to 0.58 for dry bean. The GHI values of modern crop cultivars are commonly higher than old traditional cultivars for major field crops (Ludlow and Muchow, 1990). Cox and Cherney (2001) reported average GHI values of 0.50 for 23 forage corn hybrids. Miller *et al.* (2003) reported GHI values of 0.39 for pea (*Pisum sativum* L.), 0.37 for lentil (*Lens culinaris* Medik.), 0.41 for chickpea (*Cicer arietinum* L.), 0.28 for mustard (*Brassica juncea* L.), and 0.38 for wheat grown on loamy soil. Winter and Unger (2001) reported that sorghum GHI values varied from 0.39 to 0.45, depending on type of tillage system adopted. Rice GHI values varied greatly among cultivars, locations, seasons, and ecosystems, and ranged from 0.35 to 0.62, indicating the importance of this variable for yield simulation (Kiniry *et al.*, 2001). Rao *et al.* (2002) reported GHI values of soybean ranged from 0.37 to 0.45 with a genotypic mean of 0.43. Rao and Bhagsari (1998) reported similar ranges for GHI values for soybean grown in Georgia. Lopez-Bellido *et al.* (2000) reported that GHI values for wheat varied from 0.41 to 0.45 (mean value of 0.44) depending on tillage methods, crop rotation, and N rate.

The limit to which harvest index can be increased is considered to be about 0.60 (Austin *et al.*, 1980). Hence, cultivar with low harvest indexes would indicate that further improvement in partitioning of biomass would

be possible. On the other hand, cultivars with harvest indexes between 0.50 and 0.60 would probably not benefit by increasing harvest index (Sharma and Smith, 1986).

Genetic improvement in annual crops such as wheat, barley, corn, oat, rice, and soybean has been reported due to improved dry weight as well as GHI (Austin *et al.*, 1980; Cregan and Yaklich, 1986; Feil, 1992; Payne *et al.*, 1986, 2000; Tollenaar, 1989; Wych and Rasmusson, 1983; Wych and Stuthman, 1983). Peng *et al.* (2000) reported that genetic gain in rice cultivars released before 1980 was mainly due to improvement in GHI, while increases in total biomass were associated with yield trends for cultivars developed after 1980. The cultivars developed after 1980 had relatively high GHI values and further improvement in GHI was not achieved. These authors also reported that further increases in rice yield potential would likely occur through increasing biomass production rather than increasing GHI. Tollenaar *et al.* (1997) reported that GHI values of corn were 0.41 at low N rates (no added N) and 0.45 at higher N rates (150 kg N ha^{-1}) across two hybrids. The GHI values of upland rice genotypes were influenced by N fertilization (Table III). Overall, increases in GHI values were 16% at high N rates compared with low N rates. These results indicate that higher GHI values can be obtained with proper N management in annual crops.

VI. NITROGEN UPTAKE AND PARTITIONING

Uptake of N in crop plants is highest among essential plant nutrients. However, N uptake is second to K in some cereals crops such as rice (Fageria *et al.*, 2003a). Nitrogen is mainly absorbed as NO_3^- and NH_4^+ by roots. In oxidized soils, NO_3^- is the dominant form and absorption of this form predominates. In reduced soil conditions, such as flooded rice, NH_4^+ may predominate in the absorption process. The topic of NH_4^+ vs. NO_3^- nutrition of plants has been extensively reviewed (Hayes and Goh, 1978; Hageman 1984; Mengel *et al.*, 2001). It has been proven that most annual crops grow best when supplied mixtures of NH_4^+ and NO_3^- under controlled conditions (Bock *et al.*, 1991; Goos *et al.*, 1999; Wang and Below, 1996).

Plants can excrete H^+ or OH^+ from roots in amounts depending on N supply and availability (Hedley *et al.*, 1982). Differences in H^+ or OH^- release in the rhizosphere have also been reported between plant species and also due to N uptake and assimilation (Bolan *et al.*, 1991; Haynes, 1990; Logan *et al.*, 1999). These plant-induced changes in pH of the rhizosphere can have a major impact on nutrient acquisition and plant growth (Aguilar and Diest, 1981; Gahoonia and Nielsen, 1992). Among N-related traits, N uptake and its subsequent translocation to leaves appear to be critical to many plants

Table III
Grain Harvest Index (GHI) as Influenced by N Rate and Upland Rice Genotype

Genotype	Low N rate (zero mg kg^{-1})	High N rate (400 mg kg^{-1})
CRO 97505	0.48a	0.54abcd
CNAs 8993	0.52a	0.57a
CNAs 8812	0.43a	0.49abcd
CNAs 8938	0.43a	0.52abcd
CNAs 8960	0.45a	0.54abc
CNAs 8989	0.49a	0.56abc
CNAs 8824	0.47a	0.50abcd
CNAs 8957	0.40a	0.56ab
CRO 97422	0.40a	0.50abcd
CNAs 8817	0.51a	0.48abcd
CNAs 8934	0.39a	0.46cd
CNAs 9852	0.36a	0.55abc
CNAs 8950	0.43a	0.52abcd
CNA 8540	0.41a	0.48abcd
CNA 8711	0.42a	0.49abcd
CNA 8170	0.41a	0.33e
Primaveira	0.49a	0.55abc
Canastra	0.36a	0.44d
Carisma	0.37a	0.47bcd
Average	0.43	0.50
F-Test		
N Rate (N)	*	
Genotype (G)	**	
N X G	**	
CV (%)	9	

*, **Significant at the 5 and 1% probability level, respectively. Means followed by the same letter in the same column are not significantly different at the 5% probability level by Tukeys test.

(Imsande and Touraine, 1994). Dhugga and Waines (1989) suggested that N absorption may be a limiting factor in N accumulation.

A. Nitrogen Concentration

Nutrient uptake in crop plants is mainly measured by plant tissue analysis. Plant tissue analysis is the determination of elemental concentration in samples from particular parts or portions of a crop sampled at certain times or stages of morphological development (Fageria, 2003). Concentration is usually expressed on dry weight basis. Generally, concentration values are used to diagnose nutrient sufficiency, deficiency, or excess in crop plants. Plant tissue tests have been successfully used to determine N status of several grain crops (Baethgen and Alley, 1989a; Blackmer and Schepers, 1994;

Donohue and Brann, 1984; Flowers *et al*., 2003; Follett *et al*., 1992; Roth *et al*., 1989; Smeal and Zhang, 1994). Tissue analysis has been widely used to determine in-season N status and to correct N deficiency in wheat (Baethgen and Alley, 1989a; Flowers *et al*., 2003). In wheat, N concentrations in the whole plant at the Zadoks *et al*. (1974) growth stage 30 have been identified as the critical value because applying topdress N at this stage has been shown to be a very efficient means of supplying N to optimize yield and NUE (Baethgen and Alley, 1989b). Critical whole plant (wheat) N concentrations of 35.0 g kg^{-1} (Roth *et al*., 1989), 36.0 g kg^{-1} (Fox *et al*., 1994), and 39.5 g kg^{-1} (Baethgen and Alley, 1989b) have been reported. In rice, Ying *et al* (1998) reported that adequate N concentration should be 39.4 g kg^{-1} at midtillering, 13.4 g kg^{-1} at flowering, and 10.8 g kg^{-1} at maturity. Nutrient concentrations are influenced by plant age, plant part analyzed (leaves, shoots, or whole top), cultivar, water and nutrient availability in the soil, and control of pests. Although nutrient concentrations are influenced by several soils, plant, and climatic factors, plant tissue concentrations are still relatively more stable and useful parameters compared with soil analysis for identifying nutritional status of crop plants. Plants have a remarkable ability of regulating nutrient uptakes according to their growth demands. Significant variation in nutrient concentrations in the growth medium did bring very small changes in nutrient concentrations in plant tissue (Smith, 1986). Hence, it can be concluded that concentrations of most nutrients in plant tissues are restricted to fairly narrow ranges.

Nutrient concentrations can be extrapolated or used for identifying nutritional disorders in the same crop species from different agroecological regions. This is possible because nutrient uptake in plants is an integral part of all factors affecting nutrient availability. One of the most important considerations in defining adequate concentrations is plant age. A relationship between dry matter yield of shoots or grain and N concentration in the shoot or grain of lowland rice at different growth stages was determined (Table IV). Based on this relationship, optimum N concentrations in shoots at different growth stages and in the grain at harvest were determined. Optimum N concentrations in shoots varied from 43.4 g kg^{-1} at initiation of tillering to 6.5 g kg^{-1} at physiological maturity. The N concentration in the grain at physiological maturity was 11 g kg^{-1}. Hence, optimal N concentration in shoots of rice decreased with advanced plant age. During grain filling, N content of non-grain tissue generally decreases while grain N content increases (Bauer *et al*., 1987; Wilhelm *et al*., 2002). However, shoot dry weight increased with age advancement up to the flowering growth stage and then decreased (Fageria, 2003). Decreases in shoot dry weight at harvest was related to translocation of assimilate to the panicle from flowering to maturity (Black and Siddoway, 1977; Fageria *et al*., 1997a,b). In rice, 60–90% of the total C accumulated in panicles at the time of harvest was

Table IV
Relationship between Dry Matter Yield of Shoot or Grain (Y) and N Concentration in Shoot or Grain at Different Growth Stages in Lowland Rice (Values are Averages of 3 Years Field Experimentation)

Plant growth stage	Regression	R^2	Optimum N Conc. for maximum shoot or grain yield (g kg^{-1})
IT (22)[a]	$Y = -439.4654 + 22.5403X - 0.0946X^2$	0.39^{NS}	43.4
AT (35)	$Y = -8974.3480 + 586.9736X - 8.4265X^2$	0.74^{*}	34.6
IP (71)[a]	$Y = 211.7915 - 34.9390X + 28.1748X^2$	0.88^{**}	12.7
B (97)	$Y = -36286.13 + 7325.2430X - 285.4674X^2$	0.77^{*}	12.8
F (112)	$Y = -44383.16 + 10690.71X - 485.6974X^2$	0.94^{**}	11.0
PM (140)	$Y = -100159.00 + 33792.63X - 2605.362X^2$	0.94^{**}	6.5
PM (140)[b]	$Y = 1141085.70 + 27046.20X - 1237.72X^2$	0.78^{*}	10.9

^{*,**,NS}, Significant at the 5 and 1% probability level and nonsignificant, respectively. IT, initiation of tillering; AT, active tillering; IP, initiation of panicle; B, booting; F, flowering; PM, physiological maturity. Values in the parentheses represent age of the plants in days after sowing.
[a]Where regression equation was nonsignificant or β_1 regression coefficient was negative, average value across the N rates was considered as adequate N concentration for maximum yield.
[b]In this line, values are for grain yield.
Source: Adapted from Fageria, (2003).

derived from photosynthetic after heading, and the flag leaves are the organs that contributes most to grain filling (Yoshida, 1981).

Adequate concentrations, defined as N concentration ranges in specific plant parts, of N in major field crops is given in Table V. Changes within this range of concentrations do not increase or decrease growth or production. These N concentration ranges are also termed as intermediate, satisfactory, normal, or sufficient. It is usually considered that fertilizer practices need not change if nutrient concentrations fall within this classification. Another term that is very commonly used for interpretation of plant tissue tests is critical nutrient range. Critical nutrient concentration range is defined as the nutrient concentration at which a 10% loss of plant growth occurs. This 10% value has been chosen to agree with significant levels of statistical analysis (Riga and Anza, 2003). On a physiological basis, critical leaf nutrient levels indicate the minimum amount of cell nutrient concentration that allows for maintenance of metabolic functions at non-limiting growth rates (Riga and Anza, 2003). The 10% yield reduction limit also approximates economic level of fertilizer addition for annual crops (Fageria *et al.*, 1997a).

Concentrations of N in most tissues of crop plants decreased with advancement of plant age (Fig. 4). This was as expected because with increasing plant age, more dry matter was produced which diluted the concentration of

Table V
Adequate N Concentration in Plant Tissue of Principal Cereal and Legume Crops

Crop species	Growth stage	Plant part	Adequate N conc. (g kg^{-1})
Wheat	Tillering	Leaf blade	43–52
Wheat	Shooting	Leaf blade	36–44
Wheat	Heading	Whole tops	21–30
Wheat	Flowering	Leaf blade	27–30
Barley	Tillering	Leaves	47–51
Barley	Shooting	Leaves	45–47
Barley	Heading	Whole tops	20–30
Barley	Flowering	Leaves	29–35
Lowland rice	Initiation of tillering	Whole tops	44–46
Lowland rice	Active tillering	Whole tops	31–35
Lowland rice	Panicle initiation	Whole tops	12–15
Lowland rice	Booting	Whole tops	10–13
Lowland rice	Flowering	Whole tops-grains	9–11
Lowland rice	Physiological maturity	Whole tops-grains	6–7
Corn	30 to 45 DAE[¶]	Whole tops	35–50
Corn	Before tasseling	Leaf blade below whoral	30–35
Corn	Silking	BOAC[§]	>32
Sorghum	Seedling	Whole tops	35–51
Sorghum	Early vegetative	Whole tops	30–40
Sorghum	Vegetative	YMB[‡]	32–42
Sorghum	Bloom	3BBP[†]	33–40
Soybean	Prior to pod set	UFDT[♥]	45–55
Dry bean	Early flowering	UMB[♦]	52–54
Cowpea	39 DAS[♣]	Whole tops	28–35
Cowpea	Early flowering	PUMB[♪]	11–17
Peanut	Early pegging	Upper stems and leaves	35–45
Cassava	Vegetative	UMB	50–60
Potato	42DAE	UMB + P[♀]	40–50
Potato	Early flowering	UMB + P	55–65
Potato	Tuber half grown	UMB + P	30–50
Cotton	First flowering	YMB	38–45

[¶]DAE, days after emergence.
[♣]DAS, days after sowing.
[§]BOAC, blade opposite & above cob.
[‡]YMB, youngest (uppermost) mature leaf blade.
[†]3BBP, third blade below panicle.
[♥]UFDT, upper fully developed trifoliate.
[♦]UMB, uppermost blade.
[♪]PUMB, petiole of uppermost mature leaf blade.
[♀]UMB + P, uppermost mature leaf blade + petiole.
Sources: Piggott (1986), Reuter (1986), Small and Ohlrogge (1973), Fagria *et al.* (1997a), and Fageria (2003).

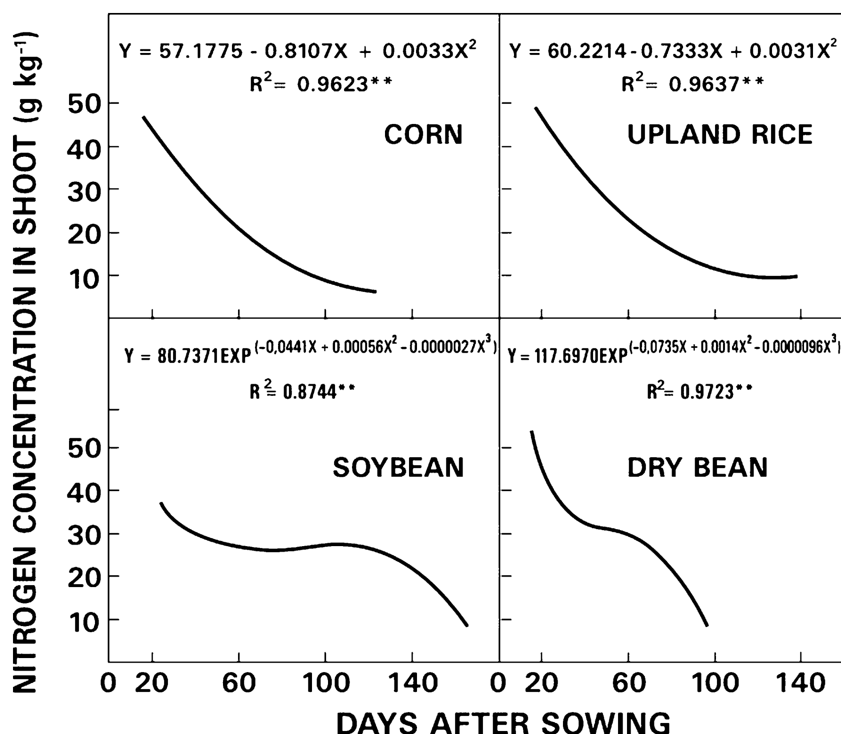


Figure 4 Relationship between N concentration in shoot of corn, upland rice, soybean, and dry bean as a function of plant age. Adapted from Fageria (2004).

nutrients accumulated (Fageria *et al.*, 1997b). Maman *et al.* (1999) reported that N concentrations were higher during vegetative stages of growth and decreased with plant age in pearl millet. Nitrogen concentrations were higher when leaves were analyzed rather than whole plant top. These values can be affected by several factors but may serve as general guidelines for interpretation of plant analysis results.

Comparison of crop responses to N deficiency requires quantification (Delden, 2001). To that end, Lemaire *et al.* (1989) proposed an N nutrition index (NNI), defined as NNI = Actual crop N/critical crop N, where the critical crop N barely limits crop growth rate. Calculated mean NNI values over time should be at maximum values of 1 because crop growth rates are at their maximum when NNI ≤ 1 and NNI >1 indicates luxury consumption (Lemaire *et al.*, 1989). This index has also been used in various studies to quantify N deficiency (Belanger *et al.*, 1992).

Nitrogen concentration in plant leaves has been associated with grain yield. Higher N concentrations later in the plant growth stages have advantage because higher N may be translocated to grain and ultimately higher yields (Boote *et al*., 2003). Another aspect of leaf N concentration on photosynthesis is not necessarily the higher initial N concentration, but the slower N mobilization (stay green) during seed filling. This slower mobilization serves to maintain photosynthesis longer during grain filling of improved vs. older cultivars (Wells *et al*., 1982). Boerma and Ashley (1988) reported that improved soybean cultivars maintained higher leaf and canopy photosynthesis during grain filling than did old soybean cultivars. Higher N mobilization into grain also resulted in higher grain harvest index (Boote *et al*., 2003).

B. Nitrogen Accumulation

When dry matter or grain yield is multiplied by concentration, the results are a measure of nutrient uptake and expressed in accumulation or uptake units. Under field conditions, the nutrient uptake or accumulation unit is kg ha^{-1} for macronutrients and g ha^{-1} for micronutrients. Nutrient uptake values are useful indicators of soil fertility depletion and are related to crop yield levels. Nutrient accumulation patterns in crop plants followed dry matter accumulation (Fig. 5). Sims and Place (1968), Moore *et al*. (1981), and Ntamatungiro *et al*. (1999) reported that the amount of N accumulated generally paralleled dry matter accumulation and increased with plant age.

A study was conducted at the National Rice and Bean Research Center of EMBRAPA, Santo Antônio de Goiás, Brazil to study the association between dry matter and grain yield of lowland rice and N accumulation (Table VI). The N uptake into shoots as well as into grain of lowland rice was significantly related to shoot dry weight and grain yield (Table VI). Osaki *et al*. (1992, 1996), Shinano *et al*. (1995), and Nakamura *et al*. (1997) also reported accumulation of N in cereals, including rice dry matter production, is closely related to N accumulation. Nitrogen uptake as well as shoot dry weight increased up to the flowering stage (Fageria, 2003). At harvest, more N was accumulated in grain than in dry matter. Yoshida (1981) reported that during plant ripening, about 70% of the N absorbed by the straw will be translocated to the grain, and maintain N contents of the grain at certain percentages. Nitrogen absorbed by rice during the vegetative growth stage contributes to growth during the reproductive and grain filling growth stages via translocation (Bufogle *et al*., 1997a,b; Mae, 1986; Norman *et al*., 1992; Shoji *et al*., 1986).

At physiological maturity growth stage, N uptake as well as shoot dry weight was decreased compared to the flowering growth stage

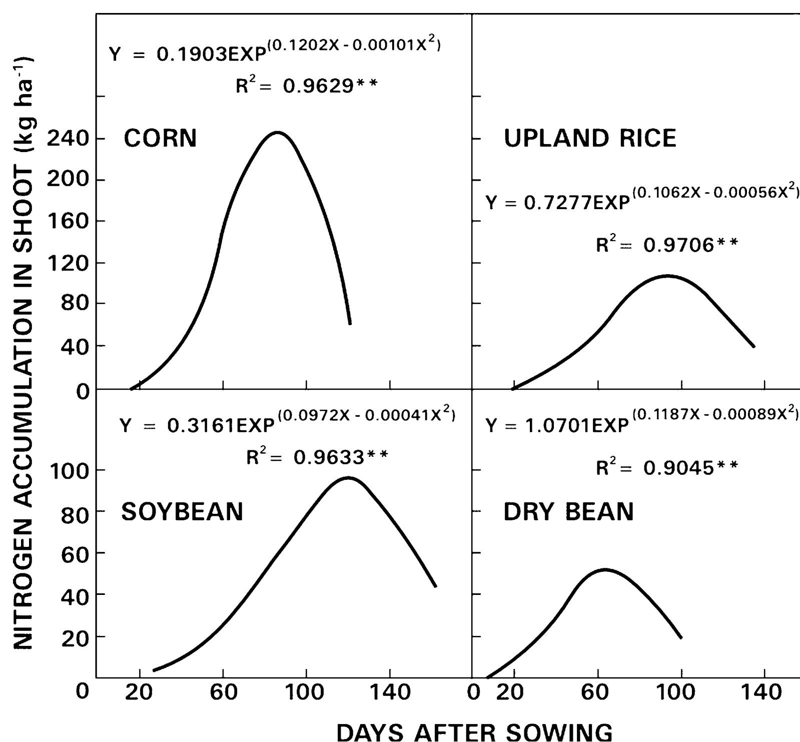


Figure 5 Relationship between N accumulation in shoot of corn, upland rice, soybean, and dry bean as a function of plant age. Adapted from Fageria (2004).

(Fageria, 2003). Decreases in shoot dry matter at harvest may be related to photosynthetic product translocation to grain during the interval from flowering to harvest (Fageria and Baligar, 2001a,b). To produce 1.0 ton of rice, 23 kg N was accumulated in the grain and straw (Fageria and Baligar, 2001a). According to Yoshida (1981), the amount of N required to produce 1.0 ton rough rice is about 20 kg N. Mae (1997) reported that the amount of N uptake needed to produce 1.0 ton of rough rice was 15–17 kg N for an average yield of 5–6 Mg ha^{-1} and 19 kg N for high yielding rice (6–7 Mg ha^{-1}). Relatively higher variation (88% and about 94% in shoot dry weight) due to N concentration at initiation of panicle, and flowering or physiological maturity (Fageria, 2003), indicating that these three growth stages were more critical during crop growth cycle in determining N status of rice crop for maximum shoot weight. Higher r values (coefficient of correlation) or higher variation in grain yield (Table VI) due to N uptake in shoots as well as grain during panicle initiation, flowering, and physiological maturity growth stages further provided evidence of the importance of these three

Table VI
Relationship between Grain Yield (Y) and N Uptake in the Shoot and Grain of Lowland Rice at Different Growth Stages (Values Are Averages of Three Years Field Experimentation)

Plant growth stage	Regression	R^2	N uptake for maximum shoot or grain yield (kg ha^{-1})
IT (22)	$Y = 166.46 + 9.4552X - 0.1565X^2$	0.61^{NS}	16
AT (35)	$Y = -391.29 + 63.8885X - 0.5898X^2$	0.93**	54
IP (71)	$Y = 40.32 + 101.2576X - 0.3939X^2$	0.97**	129
B (97)	$Y = -2069.44 + 185.7829X - 0.6725X^2$	0.94**	138
F (112)	$Y = -367.39 + 167.8636X - 0.4528X^2$	0.97**	185
PM (140)	$Y = -2330.74 + 335.1191X - 2.3641X^2$	0.99**	71
PM (140)[a]	$Y = -3547.09 + 261.4988X - 1.7099X^2$	0.99**	76

**NS, Significant at the 1% probability level and nonsignificant, respectively. IT, initiation of tillering; AT, active tillering; IP, initiation of panicle; B, booting; F, flowering; PM, physiological maturity. Values in the parentheses represent age of the plants in days after sowing. Where regression equation was nonsignificant, average value across the N rates was considered as quantity of N uptake for maximum yield.
[a]In this line, values are for grain yield.
Source: Adapted from Fageria (2003).

growth stages in determining N status of lowland rice for maximum shoot or grain yield. These findings mean that plant sampling for determining N status of rice plant can be taken at any of these three growth stages.

Nitrogen accumulation values in straw and grain of major field crops are given in Table VII. Uptake values varied from crop species to species, higher in grain compared to straw. This indicates that grains are greater sinks for N accumulation compared with other parts of the tops. Generally, N uptake in grain has positive significant associations with grain yield (Fageria and Baligar, 2001a, López-Bellido *et al.*, 2003). Hence, improving N uptake in grain may lead to improved grain yield.

C. Nitrogen Harvest Index

Nitrogen harvest index (NHI) is defined as partitioning of total plant N into grain. Amount of N remobilized from storage tissues is important in grain NUE and varies among genotypes and appears to be under genetic control (Moll *et al.*, 1982; Dhugga and Waines, 1989). Normally, NHI is expressed in percentages. The NHI values are calculated by the equation, NHI = (N uptake in grain/N uptake in grain + straw) $\times$ 100. In calculations of NHI, N uptake of above ground plant parts (grain + straw) is considered and roots are not included. This index is very useful in

Table VII
Nitrogen Uptake in Stover and Grain of Major Field Crops

Crop species	N uptake in stover (kg ha^{-1})	N uptake in grain (kg ha^{-1})	Stover yield (kg ha^{-1})	Grain Yield (kg ha^{-1})	Reference
Upland rice	56	70	6,343	4,568	Fageria (2001)
Upland rice	79	80	6,642	4,794	Fageria *et al.* (1997a)
Upland rice	35	37	4,341	2,716	Ohno and Marur (1971)
Lowland rice	66	74	9,423	6,389	Fageria and Baligar (2001a)
Lowland rice	49	82	8,005	7,093	Fageria and Prabhu (2003)
Lowland rice	75	143	9,000	14,600	De Datta and Mikkelsen (1985)
Corn	72	127	11,873	8,501	Fageria (2001)
Corn	110	150	10,000	9,400	Jacobs (1998)
Dry bean	2,338	3,859	17	124	Fageria *et al.* (2004a)
Wheat	20	55	3,400	2,700	Jacobs (1998)
Wheat	51	104	5,120	3,357	Woolfolk *et al.* (2002)
Barley					
Sorghum	73	55	6,700	3,800	Jacobs (1998)
Soybean					
Faba bean	19	89	1,443	2,007	López-Bellido *et al.* (2003)

measuring N partitioning in crop plants, which provides an indication of how efficiently the plant utilized acquired N for grain production (Fageria *et al.*, 2003a). Genetic variability for NHI exists within crop genotypes and high NHI is associated with efficient utilization of N (Fageria and Baligar, 2003b). Thus the variations in NHI are characteristic of genotypes and this trait may be useful in selecting crop genotypes for higher grain yield (Fageria *et al.*, 2003a). Dhugga and Waines (1989) reported that genotypes which accumulate little or no N after anthesis had low grain yields and low NHE.

The NHI values varied from crop species to crop species and among genotypes of the same species. Mean NHI values of 82% were reported for faba bean (Kaul *et al.*, 1996; López-Bellido *et al.*, 2003). Soil and crop management practices also influence NHI. In winter wheat, NHI values ranged from 51–54% for moldboard plowed conditions compared with 58–64% for no-till conditions (Rao and Dao, 1996). These results indicated that subsurface N fertilizer placement in plowed plots had no significant effect on grain yield or grain N content. In contrast, N banded below the seed in no-till conditions improved both grain yield and grain N contents compared with surface broadcast N (Rao and Dao, 1996).

D. Nitrogen Use Efficiency Versus Grain Yield

As mentioned earlier, NUE is defined in several ways in the literature. The question is how the NUEs are related to crop yields. Nitrogen is the principal constituent of numerous organic compounds like amino acids, proteins, nucleic acids, and compounds of secondary plant metabolism such as alkaloids (Mengel *et al*., 2001). Efficiency of N uptake and use relative to the production of grain requires that processes associated with absorption, translocation, assimilation, and redistribution of N operate effectively (Moll *et al*., 1982). Among these processes, uptake of N in higher amounts by plants and its translocation to grain is crucial for increasing yields. A relationship was determined between grain yield and NUEs of 19 upland rice genotypes tested under two N rates (zero [low] and 400 mg [high]) (Fig. 6). Agronomical, agrophysiological, apparent recovery, and utilization efficiencies had significant positive associations with grain yield. Similarly, in a field experiment, N utilization efficiency of lowland rice genotypes grown in field experiments had significant positive quadratic association with grain yield (Fig. 7). López-Bellido *et al*. (2003) also reported that N use efficiency in faba bean was higher in the years with higher seed yield and higher N uptake. However, plant N accumulation and grain yield generally had positive quadratic relationships (Cassman *et al*., 2002; Fageria and Baligar, 2001a), which means that diminishing returns appear in the conversion of plant N to grain as yields approach yield potential ceilings.

E. Nitrogen Interaction with Other Nutrients

Nutrient interaction in crop plants is probably one of the most important factors affecting yields of annual crops. Nutrient interactions may be positive, negative, or no interaction (Fageria, 1983, 1989; Fageria *et al*., 1997a). These interactions can be measured in terms of crop growth and nutrient concentrations in plant tissue. Soil, plant, and climatic factors can influence the type of interaction. In nutrient interaction studies, all other factors should be at optimum levels except the variation in level of nutrient under investigation. Nutrient interactions can occur at the root surface or within the plant. Interactions at the root surface are usually due to formation of chemical bonds by ions and precipitation or complexes. One example of this type of interaction is liming of acidic soils to decrease the concentration of almost all the micronutrients except Mo (Fageria and Zimmermann, 1998). The second type of interaction is between ions with chemical properties so sufficiently similar that they compete for sites of absorption, transport, and function on plant root surfaces or within plant tissues. Such interactions are

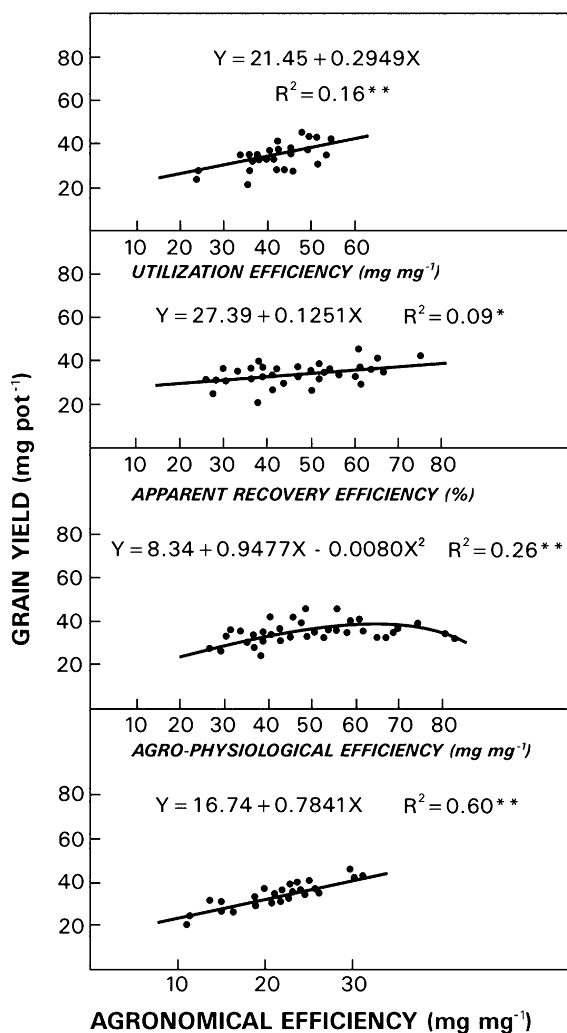


Figure 6 Relationship between nitrogen use efficiencies and grain yield of upland rice (Fageria *et al.*, 2004b).

more common between nutrients of similar size, charge, and geometry of coordination and electronic configuration (Robson and Pitman, 1983).

The interactions vary from nutrient to nutrient and from crop species to species and sometimes among cultivars of same species. Therefore, this issue is very complex in mineral nutrition and not well understood for

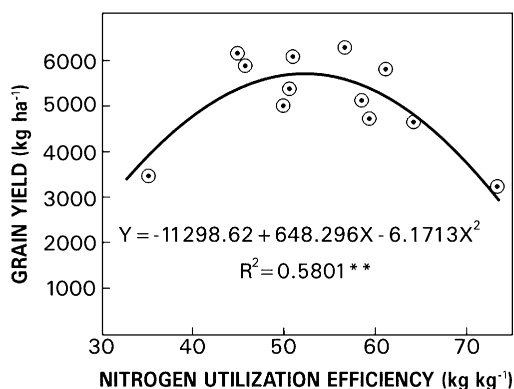


Figure 7 Relationship between nitrogen utilization efficiency and grain yield of lowland rice.

annual crops and still a debatable issue. However, published information on interactions of N with other nutrients is reviewed. This information may be helpful for improving NUE in crop plants.

Positive interactions between N and other nutrients have been reported (Terman *et al.*, 1977; Wilkinson *et al.*, 1999). Schulthess *et al.* (1997) reported that accumulation of N and P in shoot and grain of wheat was positively associated. The positive interactions of N with P, K, Ca, Mg, Zn, Cu, Mn, and Fe may be associated with improved yield with additions of N (Tables VIII and IX). Pederson *et al.* (2002) reported that N concentration was highly correlated with P, Cu, and Zn concentrations in aboveground plant parts of ryegrass (*Lolium multiforum* Lam.). These authors concluded that improvements in N fertility would improve P, Cu, and Zn concentration in plants. The mechanisms involved are not well understood, but several soil and plant related mechanisms have been reported (Adams, 1980). It has been reported that N improves root growth, which may also improve uptake of other nutrients (Wilkinson *et al.*, 1999).

Nitrogen also has positive interactions with S in crop plants (Zhao *et al.*, 1997). Nitrogen has strong influences on S assimilation and vice versa (Hawkesford, 1995). Jackson (2000) reported that canola (*Brassica napus* L.) response to N fertilization reached a plateau at about 200 kg N ha^{-1} without S addition. However, canola responded almost linearly to N application up to 250 kg N ha^{-1} when 22 kg S ha^{-1} was added. Eagle *et al.* (2000) reported that K deficiency contributed to lower responses of rice to applied N and consequently lower yields were obtained. Similarly, Pettigrew *et al.* (1996) reported that K deficiency affected the ability of cotton to utilize soil N and yields were reduced. Hence, positive interactions between N and K in crop plants exist.

Table VIII
Dry Weight of Shoot and P, K, Ca, and Mg Accumulation in Shoot of 60 Days Old Dry Bean Plants as Influenced by N Rates

N rate (kg ha^{-1})	Shoot dry weight (kg ha^{-1})	P Accumulation (kg ha^{-1})	K Accumulation (kg ha^{-1})	Ca Accumulation (kg ha^{-1})	Mg Accumulation (kg ha^{-1})
0	220.0	0.6	4.4	4.1	1.0
40	493.8	1.4	9.4	8.2	2.1
80	813.8	1.6	17.2	12.8	3.2
120	827.5	2.1	16.7	12.9	3.3
160	1260.0	2.9	28.6	18.4	5.1
200	1658.8	3.4	33.2	24.9	6.5
R^2	0.8328**	0.8058**	0.7076**	0.7942**	0.7855**

**Significant at the 1% probability level.

Table IX
Influence of N on Accumulation of Micronutrients in the Shoot of 60 Days Old Dry Bean Plants

N rate (kg ha^{-1})	Zn (g ha^{-1})	Cu (g ha^{-1})	Mn (g ha^{-1})	Fe (g ha^{-1})
0	14.0	3.0	43.3	57.9
40	27.7	5.2	115.9	142.8
80	38.4	8.9	156.9	225.4
120	42.1	9.6	153.3	219.0
160	62.0	15.0	222.1	365.1
200	88.5	18.7	361.8	519.1
R^2	0.7937**	0.7782**	0.8786**	0.8335**

**Significant at the 1% probability level.

VII. MANAGEMENT PRACTICES TO IMPROVE NITROGEN USE EFFICIENCY

Adopting appropriate N management strategies is crucial for improving NUE and efficient crop production. These management strategies involved manipulation of soil, plant, climatic, and fertilizer variables in favor of maximum economic crop yields. It is not easy to bring appropriate balances among these crop production variables. Because these variables vary from region to region, crop to crop, and social economical conditions of the growers, interactions among these variables still make this concept difficult to understand. However, near or approximate balances are possible among crop production factors with the use of available research data for different crops under different agroecological regions. The summation of

best N management practices are discussed in this section. By adopting these practices, it is possible to improve crop yields and enhance NUE.

A. Soil Chemistry Modification

Soil acidity is a major constraint to crop production for large areas worldwide. Soils become acidic during geological evolution, especially in areas of high rainfall because bases are leached to lower profiles leaving surface layers acidic. Furthermore, acidity is associated with release of protons (H^+) during the transformation and cycling of C, N, and S in soil plant systems (Bolan and Hedley, 2003). Sumner and Noble (2003) reported that top soils affected by acidity account for 30% of the total ice free land areas of the world, with the Americas, Africa, and Asia accounting for the largest portions. In tropical South America, 85% of the soils are acidic, and approximately 850 million ha of this area are under-utilized (Fageria and Baligar, 2001b). Theoretically, soil acidity is measured in terms of H^+ and Al^{3+} concentrations in soil solutions. Practicality for crop production, soil acidity involves many factors which adversely affect plant growth and development. Plant growth on acidic soils can be limited by deficiencies of N, P, K, Ca, Mg, or Mo; toxicity of H, Al, or Mn; reduced organic matter breakdown and nutrient cycling by microflora; and reduced uptake of nutrients by plant roots and inhibition of root growth (Marschner, 1991). In Brazilian Oxisols, deficiencies of most essential macro- and micronutrients have been reported for the production of upland rice, corn, wheat, dry bean, and soybean (Fageria and Baligar, 1997). Positive effects of liming on crop growth may be associated with amelioration of one or more of the above-mentioned factors (Haynes, 1984) and possibly from reduced weed growth (Arshad *et al*., 1997; Legere *et al*., 1994)

Soil acidity adversely affects morphological, physiological, and biochemical processes in plants and consequently N uptake and use efficiency (Baligar *et al*., 1997; Fageria *et al*., 1997; Feldman, 1980; Foy, 1984; Grewal and Williams, 2003; Raven, 1975). External pH affects root growth by influencing apoplastic auxin translocation from the zone of synthesis (i.e., root tips) to the zone of root elongation (Feldman, 1980; Raven, 1975). Excessive H^+ concentrations have been reported to cause severe reductions in shoot and root growth of wheat (Johnson and Wilkinson, 1993) and sorghum (Wilkinson and Duncan, 1989). Reduction in root growth and nodulation of alfalfa in acidic soil has been reported by Grewal and Williams (2003). Apart from H^+ toxicity, excessive Al^{3+} and Mn^{2+} as well as deficiencies of nutrients have been found to be major factors contributing to reduction in plant growth and nutrient uptake on acidic soils (Foy, 1984). Acidity also decreases N uptake and use efficiency by reducing N mineralization,

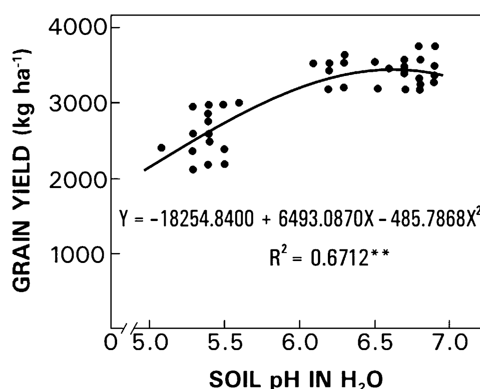
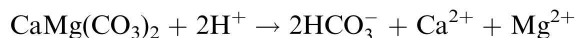


Figure 8 Relationship between soil pH and grain yield of dry bean (Fageria *et al.*, 2004a).

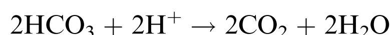
nitrification, and nodulation as well as by reducing root development of crop plants (Grewal and Williams, 2003; Menzies, 2003).

Liming is the most common and effective practice for reducing soil acidity related problems. Lime significantly increased grain yields of annual crops such as common bean, corn, and soybean grown on Brazilian Oxisols (Fageria, 2002a; Fageria and Baligar, 2001b, 2003a). Fig. 8 shows that dry bean yields increased significantly and in a quadratic fashion with increased soil pH in the range of 5.2–7.0 in a Brazilian Oxisol. Maximum yields calculated on the basis of regression equation were obtained at a soil pH of 6.7. It has been reported by many scientists that Ca added with NH_4-N increases plant NUE because of more rapid absorption, greater rates of tillering in cereals, greater metabolite deposition in seeds, and possibly increases in photosynthesis (Bailey, 1992; Fenn *et al.*, 1991, 1993, 1995). Alexander *et al.* (1991), and Sung and Lo (1990) reported that enhanced NH_4^+ absorption causes substantial increase in photosynthesis.

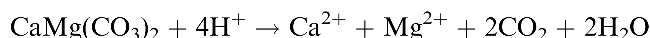
For correcting soil acidity, dolomitic lime ($CaMg(CO_3)_2$), which has both Ca and Mg, should be used. Dolomitic lime may supply both Ca and Mg and can maintain balances between these two elements. The equation below illustrates the kind of reactions that follow with the addition of dolomitic lime to an acidic soil:



$$CaMg(CO_3)_2 + 2H^+ \rightarrow 2HCO_3^- + Ca^{2+} + Mg^{2+}$$



$$2HCO_3 + 2H^+ \rightarrow 2CO_2 + 2H_2O$$



$$CaMg(CO_3)_2 + 4H^+ \rightarrow Ca^{2+} + Mg^{2+} + 2CO_2 + 2H_2O$$

The above equations show that acidity neutralizing reactions of lime occurs in two steps. In the first step, Ca and Mg react with H to replace these ions with Ca^{2+} and Mg^{2+} on the exchange sites (negatively charged

particles of clay or organic matter), forming HCO_3^-. In the second step, HCO_3^- reacts with H^+ to form CO_2 and H_2O to increase pH. The liming reaction rate is mainly determined by soil moisture and temperature along with quantity and quality of liming material. To get maximum benefits from liming or for improving crop yields, liming materials should be applied in advance of crop sowing and thoroughly mixed into the soil. Selected soil chemical properties changes with lime applied to a Brazilian Oxisol are presented in Table X.

Quantity of lime required for specific crops can be determined by laboratory methods (Adams, 1984; Fageria and Baligar, 2003a). However, the best method for lime quantity determination for a given crop is crop yield versus lime rate curves. Some of these curves developed for the dry bean, soybean, and corn in Brazilian Oxisol are presented in Fig. 9. The quantity of lime required depends on quality of liming material, crop species, soil pH, concentrations of Ca, Mg, and Al in the soil, soil type, and economic considerations. Adequate values of some acidity indexes determined for dry bean grown on a Brazilian Oxisol are presented in Table XI.

Table X
Influence of Liming on Selected Soil Chemical Properties of an Oxisol at 0–10 and 10–20 cm Depth

	Lime rate Mg ha^{-1}				
Soil property	0	12	24	F Test	CV (%)
		0–10 cm depth			
pH in H_2O	5.4c	6.8b	7.2a	**	2
Base saturation (%)	30.3c	73.9b	83.6a	**	7
H+Al ($cmol_c\ kg^{-1}$)	6.6a	2.5b	1.5c	**	12
Acidity saturation (%)	69.8a	26.9b	15.7c	**	9
Ca ($cmol_c\ kg^{-1}$)	1.8c	3.9b	4.5a	**	7
Mg ($cmol_c\ kg^{-1}$)	0.5b	1.3a	1.3a	**	8
CEC ($cmol_c\ kg^{-1}$)	9.2a	7.9b	7.5c	**	6
		10–20 cm depth			
pH in H_2O	5.1c	6.0b	6.4a	**	2
Base saturation (%)	22.1c	46.4b	56.0a	**	9
H+Al ($cmol_c\ kg^{-1}$)	7.0a	3.8b	2.9c	**	7
Acidity saturation (%)	78.5a	50.9b	39.1c	**	5
Ca ($cmol_c\ kg^{-1}$)	1.3c	2.7b	3.5a	**	10
Mg ($cmol_c\ kg^{-1}$)	0.4c	1.0b	1.1a	**	12
CEC ($cmol_c\ kg^{-1}$)	8.7a	8.3b	8.1b	**	5

*Significant at the 1% probability level. Values followed by the same letter in the same line under different lime rates are not significant at the 5% probability level by the Tukey test.
Base saturation = (Σexchangeable Ca, Mg, K/CEC at pH 8.2 × 100), where, CEC is cation exchange capacity, which is Σ of Ca, Mg, K, H, Al. Acidity saturation = (H + Al/CEC × 100)
Source: Fageria and Stone (2004).

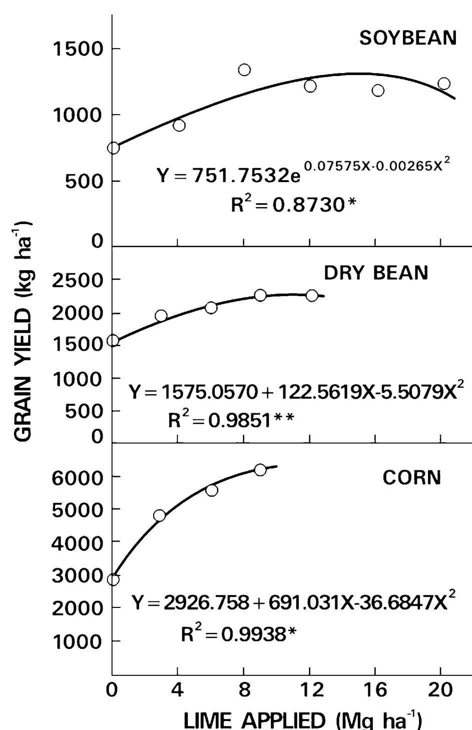


Figure 9 Influence of lime application rates on grain yield of dry bean, soybean and corn in Brazilian Oxisol. Adapted from Fageria and Stone (1999).

B. Use of Controlled Release Fertilizers and NH_4/NO_3 Inhibitors

Controlled release N fertilizers and nitrification inhibitors are potential sources for improving NUE for many crops (Shoji *et al*., 2001). Slow release characteristics of N products permit N uptake by plants according to their demand and reduce N leaching or denitrification losses. Improving N-use efficiency may reduce N fertilization rates that may markedly contribute to conservation of air and water quality (Shoji and Kanno, 1994). Common controlled release fertilizer types include sulfur-coated urea, polymer-coated water-soluble fertilizer, and low solubility and biodegradable fertilizer materials (Maynard and Lorenz, 1979).

Use of nitrification inhibitors with NH_4^+-N based fertilizers is recognized as one potential tool to improve NUE and crop yields (Ferguson *et al*., 2003; Freney *et al*., 1992; Singh *et al*., 1994). The greatest benefits

Table XI
Relationship between Soil Acidity Related Chemical Properties and Grain Yield of Dry Bean Grown on an Oxisol

Soil property	Regression equation	R^2	Value for maximum yield
pH	$Y = -17689.98 + 6327.2290X - 482.5805X^2$	0.5658**	6.6
Ca ($cmol_c\ kg^{-1}$)	$Y = 856.3713 + 1093.4790X - 135.8895X^2$	0.5742**	4.0
Mg ($cmol_c\ kg^{-1}$)	$Y = 1747.4990 + 1034.2110X$	0.6037**	1.2
H + Al ($cmol_c\ kg^{-1}$)	$Y = 2782.0960 + 200.7515X - 40.9768X^2$	0.5339**	2.4
Acidity saturation (%)	$Y = 2503.6720 + 31.5171X - 0.4643X^2$	0.5554**	33.9
CEC ($cmol_c\ kg^{-1}$)	$Y = -29633.2 + 8179.4150X - 512.9004X^2$	0.3208**	7.9
Base saturation (%)	$Y = 1049.9020 + 57.4026X - 0.4141X^2$	0.5557**	69.3
Ca saturation (%)	$Y = 927.8372 + 90.4341X - 0.9669X^2$	0.5526**	46.8
Mg saturation (%)	$Y = 1812.42 + 77.9733X$	0.5745**	15.3
K saturation K (%)	$Y = -373.6017 + 1908.5480X - 225.1399X^2$	0.3250**	4.2
Ca/Mg ratio	$Y = 7861.1270 - 2476.7290X + 269.8845X^2$	0.2821**	4.6
Ca/K ratio	$Y = 121.3962 + 310.9937X - 8.1177X^2$	0.5676**	19.1
Mg/K ratio	$Y = 917.4143 + 635.0469X - 47.4527X^2$	0.5276**	6.7

**,nsSignificant at the 1% probability level and nonsignificant, respectively. Values for maximum yield were calculated by regression equation where R^2 was significant. Where R^2 was nonsignificant and regression coefficient (β_1) was negative or regression equation was linear, original soil value was considered adequate for maximum yield. Source: Fageria and Stone (2004).

from nitrification inhibitors have been reported on coarse textured soils and soils that remain saturated with water during large parts of the crop growing season (Hoeft, 1984; Meisinger, 1984). Nitrogen is subject to leaching from coarse textured soils, and denitrification can be a dominant N loss mechanism in saturated soils. It has also been reported that beneficial effects of nitrification inhibitors are frequently observed at suboptimal N rates (Cerrato and Blackmer, 1990b).

Inhibition of nitrification retains NH_4^+-N based N fertilizers in the NH^+ form, which may be retained on cation exchange sites in the soil medium, and conserved against leaching in contrast to the readily leached NO_3-N. The nitrification inhibitor (nitrapyrin [2-chloro-6-trichloromethyl] pyridine) has been used to inhibit nitrification of urea and ammonical fertilizers (Goring, 1962). Furthermore, nitrification inhibitors also reduced N_2O emissions in winter wheat (Bronson and Mosier, 1993) and barley (Delgado and Mosier, 1996) cropping systems. Controlled release fertilizers effectively decreased NO_3^--N leaching and increased crop yields and N-use efficiency in greenhouse (Amans and Slangen, 1994; Rauch and Murakami, 1994; Shoji and Gandeza, 1992; Wang and Alva, 1996) and field experiments (Delgado *et al.*, 1998; Shoji and Kanno, 1994). The N_2O emissions were

also reported to be reduced with use of controlled release fertilizers in lysimeter and field studies (Delgado and Mosier, 1996; Minami, 1992).

Urease activity inhibitors such as nBTPT [N-(n-butyl) thiophosphoric triamide] have also been reported to decrease the rate of urea hydrolysis, preventing abrupt pH rises around fertilizer granules and consequently diminishing NH_3 volatilization losses (Watson *et al.*, 1994). Carmona *et al.* (1990) reported that 50 and 34% of the applied N remained as urea after 10 days of incubation at 18 and 25 °C, respectively. However, Rozas *et al.* (1999) reported that for slightly acidic and high organic matter soils, the use of nBTPT did not improve urea NUE in corn.

C. Soil Management

Adopting appropriate soil management practices is an important component of improving NUE, reducing cost of production, and improving crop yields. These practices are discussed in the succeeding section.

1. Source, Method, Rate, and Timing of Application

In a sound fertilizer program, appropriate sources, adequate rates, efficient methods, and application timing must be determined according to crop demand, and are vital for improving nutrient use efficiency and sustainable crop production. Improving NUE is more difficult than for any other fertilizer nutrient. This is because N mobility in soil-plant systems is high and variable. Further, many sources of addition and loss pathways of N in soil-plant systems occur, which complicates N balances and N use by plants.

Nitrogen sources and methods of application significantly influence N uptake efficiency in crop plants. Important considerations for selecting sources of N by growers are availability, economics, convenience in storage and handling, and effectiveness of the carrier. Generally, urea and ammonium sulfate are the principal sources of N fertilizers. However, several fertilizers containing N are available in the market (Table XII). In United States agriculture, anhydrous ammonia (NH_3) is an important source of N fertilizer (Harre, 1985). At normal pressures, NH_3 is a gas and is transported and handled as liquid under pressure. It is injected into the soil to prevent loss through volatilization. The NH_3 protonates to form NH_4^+ in the soil and becomes XNH_4^+, which is stable (Foth and Ellis, 1988). The major advantages of anhydrous NH_3 are its high N analysis (82% N) and low cost of transportation and handling. However, specific equipment is required for storage, handling, and application. Hence, NH_3 is not a popular N carrier in developing countries.

Table XII
Major Nitrogen Fertilizers

Common name	Formula	N (%)
Ammonium sulfate	$(NH_4)_2SO_4$	21
Urea	$CO(NH_2)_2$	46
Anhydrous ammonia	NH_3	82
Ammonium chloride	NH_4Cl	26
Ammonium nitrate	NH_4NO_3	35
Potassium nitrate	KNO_3	14
Sodium nitrate	$NaNO_3$	16
Calcium nitrate	$Ca(NO_3)_2$	16
Calcium cyanamide	$CaCN_2$	21
Ammonium nitrate sulfate	$NH_4NO_3(NH_4)_2SO_4$	26
Nitrochalk	$NH_4NO_3 + CaCO_3$	21
Monoammonium phosphate	$NH_4H_2PO_4$	11
Diammonium phosphate	$(NH_4)_2HPO_4$	18

Sources: Foth and Ellis (1988); Fageria (1989); Mengel *et al.* (2001).

The N applied during sowing should be in the NH_4^+ form. The source of N used as topdressings is less critical than N source applied at sowing. The NH_4^+ and NO_3^- forms appear to be equally effective. This is because when a crop is fully established, the NO_3^- form of N is rapidly taken up by the crop before it can be leached downward to lower soil layers where it might be lost through denitrification (De Datta, 1981). NO_3^--N is formed by nitrification of the applied fertilizer and by mineralization and nitrification of soil organic matter. The predominant form of available N in most oxidized soils is NO_3^-N. NO_3^-N is highly soluble in water, and hence, is susceptible to leaching (Wienhold *et al.*, 1995). Additional fertilizer N can be lost via denitrification, especially from high moisture or flooded soils. Denitrification losses reduce fertilizer use efficiency and are of environmental concern because of the potential role N_2O may play in stratospheric ozone depletion (Keeney, 1982).

Nitrogen fertilizers should be broadcast and mixed into soil before crops are planted. Fertilizers may also be applied in the rows below the seed at sowing and may be banded in the rows beside the seed at planting or reemergence. During postemergence, fertilizers may be side-dressed by injecting them into the subsurface and top-dressed. Rao and Dao (1996) reported that subsurface placement of urea under no-till winter wheat conditions had the potential of significantly improving N availability to plants and thereby improve NUE. Fertilizers mixed into soil or injected into subsurface are more efficient methods of N application compared to broadcast and/or left on the soil surface (Beyrouty *et al.*, 1986; Whitaker *et al.*,

1978). Beyrouty *et al*. (1986) reported 20–40% increases in fertilizer recovery at the end of the year when urea-NH_4NO_3 (UAN) was applied to the subsurface compared with surface application. Vetsch and Randall (2000) reported that no-till corn yields on fine-textured, high P testing soils can be enhanced consistently by using starter fertilizer and by injecting N below the soil surface.

Touchton and Hargrove (1982) found that incorporated or surface band-applied UAN produced considerably greater yields of corn compared with broadcast UAN. Stecker *et al*. (1993) reported corn yield increases of 5–40% for knife-injected UAN compared with broadcast UAN. Much of the yield reduction from UAN left on the soil surface without incorporation has been attributed to NH_3 volatilization (Fox and Piekielek, 1993; Mengel *et al*., 1982). Keller and Mengel (1986) measured losses of broadcast applied N fertilizer in no-till corn, and found 9–30% of the N from urea and UAN were lost, respectively. Ammonia volatilization is not the only concern when evaluating N management in no-till corn. Immobilization of surface applied N fertilizers on no-till fields also contributed to poor NUE (Kitur *et al*., 1984; Mengel *et al*., 1982).

The side-dress application of N fertilization several weeks after corn emergence maximized the efficiency of fertilizer N in many situations (Fox *et al*., 1986; Piekielek and Fox, 1992). Placement of urea or $(NH_4)_2SO_4$ in the anaerobic layer of flooded rice has been an important strategy to avoid N losses by NO_3^--N leaching and denitrification (Bouldin, 1986; Gaudin and Dupuy, 1999). Utilization of urea or $(NH_4)_2SO_4$ makes no difference in NUE because urea is quickly hydrolyzed to form NH_4^+ (Gaudin and Dupuy, 1999).

Use of adequate N rates is essential for efficient use of N fertilizer and to maintain the economic sustainability of cropping systems. Excessive use of N fertilizers is economically unfavorable because incremental increases in yield diminish with increasing amounts of N applied (Miner and Smith, 1983), and it could lead to detrimental effects on the quality of soil and water resources (Mackown *et al*., 1999). Long term N fertility studies have shown that residual soil NO_3-N increases when N fertilization rates exceeded that needed for maximum yield (Halvorson and Reule, 1994; Porter *et al*., 1996; Raun and Johnson, 1995; Westerman *et al*., 1994). Increasing levels of NO_3-N in the soil profile increases the potential of leaching NO_3-N below the root zone and into shallow water zones, creating environmental concerns (Halvorson *et al*., 2001). Overfertilization as a form of insurance is common, especially by farmers in developed countries. Power and Schepers (1989) reported that the most important factors to reduce NO_3^--N are to apply the correct amount of N fertilizer. Similarly, Dinnes *et al*. (2002) reported that fertilizer N management, particularly rate and timing of application, plays a dominant role in losses of NO_3^--N from crop root zones.

Nitrogen is a mobile nutrient in soil-plant systems. Hence, crop response curves showing yield versus N rates are most efficient and effective methods for defining N requirement of a crop. Numerous mathematical models have been proposed for describing yield responses to applied N (Anderson and Nelson, 1975; Bullock and Bullock, 1994; Cerrato and Blackmer, 1990a; Colwell, 1994; Makowski *et al*., 2001). However, a quadratic yield response to N is considered the most appropriate model in determining N rate for maximum economic yield (Fageria *et al*., 1997a). Belanger *et al*. (2000) tested three statistical models for potato—quadratic, exponential, and square root—and concluded that the quadratic model was the most appropriate for describing potato yield responses to N fertilizer. However, many workers have reported that quadratic models overestimate the responses if the maximum point on the curve is taken as the best fertilizer rate (Cerrato and Blackmer, 1990a; Colwell, 1994; Neeteson and Wadman, 1987). Similarly, Bock and Sikora (1990), Angus *et al*. (1993), and Bullock and Bullock (1994) reported that the selection of the most appropriate model for a particular cropping situation is not obvious. Development of appropriate crop response curves to applied N fertilizer requires optimal environmental conditions during crop growth, and experiments should be repeated over several years for meaningful results. Figure 10 shows the relationship between N rates and grain yield of lowland rice grown on a Brazilian Inceptisol. Maximum grain yields were obtained at about 200 kg N ha^{-1}. However, N rate at 90% of maximum yield is generally considered as an economic rate (Fageria and Baligar, 2001a), which was about 130 kg N ha^{-1}. Half of this rate should be applied at sowing and the remaining half at active tillering growth stage.

Yield goal is another criterion for determining N requirements of a crop. Yield goal must be based on experience over several years and economic considerations. In defining yield goals, adoption of crop management practices should also be given due consideration. These include cultivar yield potential, and control of diseases, insects, and weeds. Whether a crop is irrigated or grown under rain-fed conditions is also important in defining yield goals, and consequently N rate. Original soil fertility and cropping systems adopted also dictate N requirements of crops.

Yield level determines N uptake of a crop and N uptake data can be used to make N recommendations (Mullen *et al*., 2003). For example, current Oklahoma N recommendations for wheat are calculated using the equation, N rate = Yield goal (kg ha^{-1}) X 0.033, where the yield goal is based on the average wheat yield for the past 5 years, and on average, 33 kg of N is needed to produce 1000 kg of grain (Mullen *et al*., 2003). Nitrogen fertilizer recommendations for corn in the midsouth United States generally are 26 kg of N per Mg of grain production expected under irrigated conditions (Larson and Oldham, 2001). These recommendations usually call for split applications N

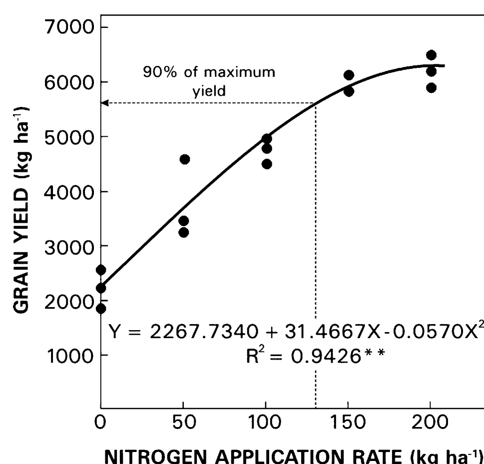


Figure 10 Influence of N application rates on grain yield of lowland rice (Fageria, *et al.* 2003b).

fertilizer, with 30–50% of the total fertilizer being applied at planting. The remainder of the N should be applied at growth stage V6 as defined by Ritchie *et al.* (1997). Lory and Scharf (2003) reported that yield based fertilizer recommendations are calculated on the basis of the following equation described by Meisinger (1984):

$N_f = (N_g - N_{gs})/FNUE$, where N_f is the estimated economically optimum N rate for selected yield goal, N_g is N content of the harvested grain, N_{gs} is soil N in the harvested grain, and FNUE is the fertilizer NUE (the proportion of fertilizer N applied to soil is recovered in the grain). Fertilizer N, N_g, and N_{gs} all must have the same units (kg ha^{-1}) and FNUE is unitless.

These approach N recommendations for United States corn crops derived by the following equation (Lory and Scharf, 2003):

N_f (kg ha^{-1}) $= 21.4$ X YG $- N_s$, where N_s is the quantity of N supplied by the soil and YG is the expected grain yield. Units are kg ha^{-1} for N_f and N_s and Mg ha^{-1} for YG.

States following this approach for making N recommendations for corn are Illinois (Hoeft and Peck, 2001), Minnesota (Schmitt *et al.*, 1998), Missouri, Nebraska (Hergert *et al.*, 1995), North Dakota (Dahnke *et al.*, 1992), Pennsylvania (Beegle and Wolf, 2000), and South Dakota (Gerwig and Gelderman, 1996). Khosla *et al* (2000) reported that for soils testing low in mineral N, 40 kg N ha^{-1} starter-band in conjunction with 130 kg N ha^{-1} side-dress N should optimize sorghum yields in most situations. Some workers have reported soil nitrate test as a good indicator of crop N requirements (Fox *et al.*, 1989; Binford *et al.*, 1992; Sims *et al.*, 1995). Rozas *et al.* (2000) reported that pre-sidedress soil nitrate test can be used to evaluate preplant

N applications as a complementary method to N budget for corn grown under different management practices. These authors reported that soil NO_3-N critical concentrations for corn ranged between 17 and 27 mg kg^{-1}.

Nitrogen is lost from soil-plant systems via leaching (Goss and Goorahoo, 1995; Paramasivam and Alva, 1997), denitrification (Burkart and James, 1999; Olson *et al.*, 1979), or runoff (Burkart and James, 1999; Gascho *et al.*, 1998). These studies indicate that more N is available for loss at any time during the crop growing season if N is applied only once during crop growth. Hence, splitting N fertilizer applications during crop growth can reduce NO_3-N leaching and improve NUE (Martin *et al.*, 1994; Mullen *et al.*, 2003; Power *et al.*, 2000; Ritter *et al.*, 1993). Mascagni and Sabbe (1991), Boman *et al.* (1995), and Woolfolk *et al.* (2002) found that split applications are extremely important to maximize crop utilization of applied fertilizer N throughout the growing season. Late-season applied N provides increased management flexibility by allowing farmers to adjust N rates according to crop growth (Woolfolk *et al.*, 2002). In-season N applied with point injection or topdressing can maintain or increase NUE compared with preplant N in wheat (Sowers *et al.*, 1994).

Split applications of N to sandy soils and in high rainfall areas are desirable. In the southeastern United States, soft red winter wheat is an important component of cropping systems (Flowers *et al.*, 2003). In this region, N leaching is very common due to sandy soils and high rainfall if N is applied at sowing time (Scharf *et al.*, 1993). In these situations, N application during the later growth stages may be appropriate to prevent N leaching and improve NUE. Baethgen and Alley (1989) reported that in densely tillered wheat, N applied at Zadoks GS 30 (Zadoks *et al.*, 1974) was the most efficient means of supplying N and optimizing grain yield. However, Weisz *et al.* (2001) showed that earlier spring N applications to poorly tillered wheat at GS 25 increased wheat yield by stimulating tiller development. These authors examined optimum N rates across wide ranges of GS 25 tiller densities and suggested a critical threshold for yield of 540 tillers m^{-2}.

The NUE is reported to be influenced by rate and time of N fertilizer application (Ellen and Spiertz, 1980; Fageria and Baligar, 1999). A possible means to increase fertilizer N efficiency for crops grown in humid regions is to apply split applications of fertilizer N. Olson and Swallow (1984) reported that split N applications improve NUE for wheat genotypes compared with pre-plant N applications. Similarly, Wuest and Cassman (1992) reported that N supplied late-season could increase grain protein and NUE for wheat compared with pre-plant applied N. Wuest and Cassman (1992) also reported that preplant ANR was 55% compared with 55–80% recovery efficiency of N applied at anthesis in wheat. Fageria and Baligar (1999) reported that agronomic efficiency of N for lowland rice was higher when

N was applied in three split applications (one-third at sowing + one-third at active tillering + one-third at panicle initiation) compared with the entire N applied at sowing. Chua *et al.* (2003) reported that ANR for cotton could be improved by restricting N additions during periods of rapid growth; that is, between early squaring and peak bloom.

When N is applied at recommended rates to crops, NUE is higher and N losses are minimum (Fageria, 1992; Kanampiu *et al.*, 1997). When N is applied at higher rates than those necessary for maximum economic yield, N accumulates in the soil profile and N losses are high (Altom *et al.*, 2002). Sharpley *et al.* (1991) reported no accumulation of N in the soil 0–180 cm profile when sorghum was fertilized at recommended rates. These authors also reported that N application rates of 180 kg N ha^{-1} resulted in increased residual NO_3-N accumulation at 150 cm soil depths for corn and sorghum. Walters and Malzer (1990) reported that 3.4 times more N leached when 180 kg N ha^{-1} was applied compared with 90 kg N ha^{-1} over 3 years of trials. Similarly, Westerman *et al.* (1994) reported that annual applications of less than 90 kg N ha^{-1} to wheat did not accumulate N in the soil profile. Fageria and Baligar (2001a) reported that maximum economic yield of lowland rice cultivated for three consecutive years in the same area was obtained with applications of 90 kg N ha^{-1}. In this study, average N utilization efficiencies at 90 kg N ha^{-1} rates were 67 kg grain produced kg^{-1} of N utilized. Timsina *et al.* (1998) reported that optimum N rates recommended by the Bangladesh Rice Research Institute to be 90 kg ha^{-1} for rice, and by the Wheat Research Center to be 120 kg ha^{-1} for wheat.

In-season applied N resulted in more efficient fertilizer use in four of five years experimentation, compared with N incorporated prior to planting winter wheat (Olson and Swallow, 1984). Similarly, Sowers *et al.* (1994) reported that in-season N applied with point injection or topdressing can maintain or increase NUE compared with preplant N for wheat. Limon-Ortega *et al.* (2000) reported that fertilizer N banded at the first node stage of growth (Zadoks stage 31) (Zadoks *et al.*, 1974) increased NUE by 3% and total N uptake by 10% compared with basal applications at planting.

Nitrogen placement methods have been tested for no-tillage corn grown in the Corn Belt, Great Plains, and mid-Atlantic regions by several workers (Eckert, 1987; Fox and Piekielek, 1987; Mengel *et al.*, 1982). These authors reported that similar N application rates of broadcast UAN produced lower yields than either injected or surface-banded UAN. The lower yields for surface broadcast UAN may have been associated with possible N losses from volatilization and immobilization (Lamond *et al.*, 1991). The period of rapid growth and nutrient uptake by grain sorghum occurs about 35 days after emergence (Vanderlip, 1993) at the eight-leaf growth stage. Side-dress applications at this stage of growth are feasible and would be beneficial for the crop.

2. Use of Animal Manures

Use of organic animal manures at adequate rates and in proper forms (well decomposed) and incorporated provides many benefits and can improve NUE for many crop plants. Organic manures have been valuable resources as fertilizers and soil amendments in crop production systems (Irshad *et al*., 2002). Studies comparing soils of organically and conventionally managed farming systems have documented higher soil organic matter and total N with the use of organic practices (Clark *et al*., 1998; Lockeretz *et al*., 1981). Addition of animal manure not only increases soil inorganic N pools, but perhaps more importantly, increases seasonal soil N mineralization available to plants (Chang *et al*., 1993; Ma *et al*., 1999; Murwira and Kirchmann, 1993). Similarly, Dao and Cavigelli (2003) reported that animal manure has long been used as a source of plant nutrients and for improving soil physical conditions of farms. Important benefits of organic manure addition are supply of nutrients, increases of organic matter contents, and improved soil physical and biological properties (Irshad *et al*., 2002; Masek *et al*., 2001). Improvement in soil physical properties such as porosity, structure, water infiltration rate, and available water, holding capacity has been reported by addition of organic manures (Sweeten and Mathers, 1985). Manures have also been found to reduce surface crusting, soil compaction, and soil bulk density (Tiarks *et al*., 1974). Organic manures have been used effectively to restore productivity of marginal, less fertile, and eroded soils (Hornick, 1982; Larney and Janzen, 1997). Larney and Janzen (1996) reported that more efficient use of N sources produced on farms (livestock manure and crop residues) may provide an alternative for producers with desires to restore their eroded soils, and at the same time, reduce their inputs of N fertilizer. These authors also stated that the mechanisms by which the amendments brought about soil restoration were largely explained by their N-supplying power. Munoz *et al*. (2003) studied N budget after multiple applications of dairy manure and concluded that during the three year study period, an average of 18% of applied manure ^{15}N was recovered in corn silage and 46% remained in the soil. Unaccounted for ^{15}N (36%) was assumed to be lost mainly by NH_3 volatilization and denitrification. These authors also reported that most (82%) of the ^{15}N remaining in soil was present in the top 30 cm, irrespective of frequency of manure application.

A complementary use of organic manures and chemical fertilizers has proved to be the best soil fertility management strategy in the tropics (Makinde and Agboola, 2002). Well decomposed farmyard manure contains about 12.9 g kg^{-1} total N, 1.0 g kg^{-1} available P, 4.5 g kg^{-1} exchangeable K, 10.8 g kg^{-1} exchangeable Ca, and 0.7 g kg^{-1} exchangeable Mg. (Makinde and Agboola, 2002). Organic manure has a greater beneficial residual effect on soils than can be derived from use of either inorganic

fertilizer or organic manure applied alone. Combined applications of organic manures and inorganic fertilizers were found best for intercropping sweet potato (*Ipomea batatas* L. Lam) and corn (Eneji *et al*., 1997), and for intercropping cassava and soybean (Makinde and Agboola, 2002). Furthermore, nutrient use efficiencies have been reported to be increased with complementary applications of organic manures and chemical fertilizers (Murwira and Kirchmann, 1993).

Although organic manures provide several benefits, use of feedlot cattle manures at high rates and/or perpetual applications of manure can lead to increased NO_3-N leaching to groundwater and P loss in surface runoff (Sharpley and Smith, 1995). Over applications of manure to relatively high productive areas can lead to greater surface and groundwater pollution than on relatively low productive areas (Sommerfeldt *et al*., 1988). This emphasizes the importance of imposing good manure management on existing practices to minimize erosion and runoff (Masek *et al*., 2001). Incorporating manure using inversion or disk tillage procedures may improve the efficiency of manure nutrient utilization by crops. However, intensive tillage often eliminates the benefits associated with conservation tillage practices such as reduced soil water evaporation, erosion and runoff control, and soil C storage (Allmaras *et al*., 2000; Dao, 1998; Gilley *et al*., 1997). These studies indicate that more research is needed to establish best methods of animal manure application under conventional and conservation tillage systems to obtain maximum benefits from this practice. Discussed in the succeeding sections are the other organic manure practices of green manuring and crop residues.

3. Adoption of Conservation Tillage System

Conservation tillage improves soil quality, which enhances N availability and utilization by crop plants (Fageria, 2002b). Several beneficial effects of conservation tillage are summarized in this section, which are related to improved NUE by crop plants, and consequently higher yields. For example, tillage is well known to accelerate the loss of soil organic matter by increasing biological oxidation, and often by increasing soil erosion (Schillinger *et al*., 1999). Because of the decline in organic matter and associated soil quality, most tillage-based farming systems in dry land environments are not sustainable over the long term (Papendick and Parr, 1997). One option for maintaining and improving soil quality is to reduce or eliminate tillage.

The no-till or minimum tillage crop production systems are becoming more common in various parts of the world, and have been reported to be helpful in improving soil quality (Conservation Technology Information Center, 1997). Soil protection from erosion losses, conservation of soil water by increased infiltration and decreased evaporation, increased use of

land too steep for conventional production, and reduction in fuel, labor, and machinery costs are among the reasons for increased use of reduced tillage systems (Doran and Linn, 1994). A review by Steiner (1974) demonstrated the value of residue management systems for conserving soil water through reduced soil water evaporation. No-tillage production results in changes of soil chemical and physical properties, including increases in soil organic matter content (Douglas and Goss, 1982), aggregate stability (Heard *et al*., 1988), and macroporosity (Blackwell and Blackwell, 1989; Lal *et al*., 1990). Collectively and individually, these changes influence plant growth (Dao, 1993; Yusuf *et al*., 1999). The changes can be detrimental, neutral, or beneficial for crop growth and yield, depending on soil texture and structure (Dick and VanDoren, 1985), climatic factors such as rainfall (Boyer, 1970), and weed control (Kapusta, 1979). In general, no-till systems have greater positive effects on crop growth and yield when used on soils characterized by low organic matter levels and on well-drained soils, rather than on poorly drained soils high in organic matter (Chastain *et al*., 1995; Johnson *et al*., 1984; Kladivko *et al*., 1986; Opoku *et al*., 1997).

Sharpley *et al*. (1991) reported that N in runoff water decreased in no-till or reduced tillage systems compared to conventional tillage. Improvement in NUE of corn planted in no-tillage systems has been reported in the Argentine Pamps (Calvino *et al*., 2003). These authors also reported that corn yield increases of 0.9 Mg ha^{-1} from the mid-1990s to 1998 related to no-tillage cultivation practices and to higher plant densities being used. Synchronization of residue N mineralization, fertilizer-N application time, and subsequent crop demand for N can improve NUE of crops planted in conservation tillage systems (Reeves *et al*., 1993).

Conflicting reports exist about N balances or use efficiency for crops grown under no-till compared with conventional tillage systems. Some workers have reported that in conservation tillage systems, fertilizer N rates have been increased to prevent yield limitations from short-term N immobilization (Wood and Edwards, 1992). However, Torbert *et al*. (2001) reported that there was no indication of N limitations in the no-tillage systems compared to the other tillage systems. It has also been reported that NO_3-N leaching losses from sandy soils can be greater under no-tillage than under conventional tillage systems because of higher moisture contents (Thomas *et al*., 1973). On the contrary, Meisinger *et al*. (1992) reported that NO_3-N leaching was not a highly efficient process in structural soils due to preferential flow through macropores, which are increased under no-till systems (Thomas *et al*., 1989). However, no-till systems generally have greater infiltration capacities than conventional tillage systems because of continuous macropores that are open at the soil surface (Unger and McCalla, 1980). Hence, initial leaching losses of surface applied N could be rapid in no-till systems if heavy rainfall occurs soon after fertilizer

applications. Conversely, fertilizer that has had time to diffuse into aggregate micropores would be protected from subsequent leaching because of the higher proportion of water flowing through the macropores system in no-till systems (Cameron and Haynes, 1986).

4. Water Management

From a global perspective, irrigation along with modern cultivars and N fertilizers has made significant contributions to increasing production of annual crops. Worldwide, about 17% of the cultivated land is irrigated, but these lands account for 40% of the world's food production (Rhoades and Loveday, 1990; FAOSAT, 1999). Surface irrigation is used in 95% of the irrigated area worldwide (Walker, 1989). Basin irrigation is a popular surface irrigation system consisting of flooding a squarish, relatively large field leveled to zero average slopes and fully surrounded by a dike to prevent runoff (Cavero *et al.*, 2001). In rainfed areas, supplement irrigation is vital for improving crop yields and NUE for some crops. Oweis *et al.* (2000) defined supplemental irrigation as the application of a limited amount of water to rainfed crops when precipitation fails to provide the essential moisture for normal plant growth. Many workers have reported that supplemental irrigation can alleviate the adverse effects of uneven distribution of rainfall during critical crop growth periods to improve and stabilize crop yields (Oweis *et al.*, 1998, 2000; Zhang and Oweis, 1999).

Adequate soil moisture during crop growth and development is fundamental to obtain high NUEs. Water deficit during crop growth may limit N movement in soil and may reduce N uptake and UE (Benjamin *et al.*, 1997). Conversely, excessive irrigation may cause leaching and denitrification and consequently lower NUE (Lehrsch *et al.*, 2001). Microbial processes in soils with given structures are adversely affected by both high and low water contents (Drury *et al.*, 2003). Grundmann *et al.* (1995) reported that the lower water limit for net N mineralization was -1.5 MPa (wilting point) while the upper limit was 75% of water-filled pore space.

Both N uptake and N fertilizer use efficiency should increase when N is retained in the upper soil profile. With greater N uptake, less N will remain in soil at harvest (Lehrsch *et al.*, 2001). Karlen *et al.* (1998) reported that to reduce NO_3-N leaching and increase NUE, corn producers should end the growing season with as little N as possible in the soil profile. In regions where high amounts of water percolates during the non-growing season, NO_3-N leaching is greatest from soil profiles with the greatest amount of N at harvest (Liang *et al.*, 1991; Zhou *et al.*, 1997). To improve N management under furrow irrigation and to protect groundwater quality, Lehrsch *et al.* (2001) concluded that N fertilizers should be placed separate from irrigation

water to allow the applied N to be used efficiently by growing corn, and to reduce NO_3-N that remains in soil profiles at season's end from leaching, and to minimize the potential for NO_3-N contamination of groundwater.

In legumes such as soybean, water stress can also reduce N_2 fixation (Serraj and Sinclair, 1996; Serraj *et al*., 1998). In C_3 plants such as soybeans, water stress reduced photosynthetic activity by closing leaves stomata, biomass production, and ultimately N-use efficiency (Souza *et al*., 1997).

Kirnak *et al.* (2003) reported that mulching may mitigate negative effects of water stress on plant growth and fruit yield of field-grown bell pepper (*Capsicum annuum* L.), especially for plants grown in semi-arid conditions. Mulching also increased the N availability to the pepper plants. Russelle *et al*. (1981) reported that maximum NUE for corn was obtained with low N rates applied during the season and for plants grown with light, frequent irrigation. Cassel Sharmasarkar *et al.* (2001) reported that the use of drip irrigation, in lieu of furrow practices, was effective for reducing water and N fertilizer use while sugarbeet productivity was sustained at high yields. No-till and minimum-till systems are more efficient than conventional-till systems for conserving precipitation in crop production systems (Peterson *et al*., 1996; Tanaka and Anderson, 1997).

D. Plant Management

Plant management is a complementary practice to soil management to improve N use efficiency in crop plants. Principal plant management practices are crop rotation, crop residue management, green manuring, use of cover crops and efficient species/genotypes, and control of diseases, insects, and weeds.

1. Crop Rotation

Use of appropriate crop rotations is an important strategy for improving NUE in crop plants. Appropriate sequences allow efficient use of soil resources, especially nutrients and water by crops to increase yields at a systems level (Gan *et al*., 2003). Rotation of legume and nonlegume crops has been recommended as an effective crop management practice for centuries (Martin and Leonard, 1967). Yield increases associated with crop rotation have been referred to as the rotation effect (Pierce and Rice, 1988), and yield declines associated with monoculture have been referred to as monoculture yield declines (Sumner *et al*., 1990; Porter *et al*., 1997). The use of crop rotations has generally been thought to reduce risk compared with monoculture systems (Helmers *et al*., 1986). Risk was defined as the failure to meet an annual pre-hectare net return target (Helmers *et al*., 2001).

A corn-soybean rotation had significantly less risk than monoculture practices (Helmers *et al.*, 2001).

Crop rotation is a planned sequence of crops growing in a regularly recurring succession on the same area of land, as contrasted to continuous culture of one crop or growing a variable sequence of crops (Soil Science Society of America, 1997). The use of crop rotation in crop production has been in existence for thousands of years. Early writers reported that crop rotation was in use in ancient Greece and Rome (Karlen *et al.*, 1994). MacRae and Mehuys (1985) reported that crop rotations were practiced during the Han dynasty of China more than 3000 years ago. In an appropriate crop rotation, a legume should be included with cereals. Legume fixes atmospheric N and could potentially reduce N requirements of succeeding cereal crops. Crop rotation is an effective disease, insect, and weeds control practice (Karlen *et al.*, 1994). Furthermore, crop rotation benefits are improved water use efficiency, increased nutrient use efficiency, reduced allelopathy, and improved soil quality.

Bullock (1992) cited many examples of different types of crop rotation systems used both in the United States and around the world, and their beneficial effects on crop yields. This author also noted that many of the factors and mechanisms responsible for so called rotation effects are not completely understood (Varvel and Wilhelm, 2003). In Brazil's central regions, upland rice and soybean or dry bean are very common in two-year crop rotations. In the United States, 80% of the corn is grown in two-year rotations with soybean, or in short (2- or 3-year) rotations with alfalfa, cotton, dry beans, or other crops (Power and Follett, 1987). Similarly, wheat-soybean double cropping systems have gained wide acceptance in the southeastern United States and Argentina (Board *et al.*, 2003). These cropping systems bring greater profitability compared with monocropped soybean (Larreche and Brenta, 1999; Wesley *et al.*, 1995). Besides greater profitability, double cropping also provides better erosion and pollution control (Elmore *et al.*, 1992; Kessavalou and Walters, 1997). Further, crop rotations also provide disease control (Whitam, 1996) and better seed quality and viability (Board *et al.*, 2003).

Types of crops grown in previous years may influence significantly soil water and nutrients available for subsequent crops. Gan *et al.* (2003) reported that durum wheat (*Triticum turgidum* L.) yields increased by 7% and grain crude protein content by 11% when grown after pulse crops rather than after spring wheat (*Triticum aestivum* L.). Other studies have reported that the narrow C/N ratios of pulse residues enhance soil N availability (Beckie and Brandt, 1997; Beckie *et al.*, 1997). The addition of crop residues with frequent inclusion in crop rotations improves physical, chemical, and biological properties of soil by increasing labile organic matter (Biederbeck *et al.*, 1994).

Nitrogen requirements of cereals are reduced when grown after legume crops. One method for quantifying the N contribution of legumes is the estimation of fertilizer replacement value (FRV) (Iragavarapu *et al.* (1997). Hesterman (1988) defined FRV as the amount of inorganic N fertilizer required to produce yields in a nonrotated crop equivalent to that obtained in the same but nonfertilized crop following a legume. Stute and Posner (1995) reported a FRV of 73 kg N ha^{-1} for corn planted after hairy vetch in a chisel plow system. Bollero and Bullock (1994) reported a FRV of 47 kg N ha^{-1} for sorghum and corn planted after hairy vetch in no-till and disk tillage systems. In the Saskatchewan Province of Canada, canola, mustard, and spring wheat grown in soil containing pea stubble receive an average of 20 kg N ha^{-1} less fertilizer than when grown in soil with spring wheat stubble (Gan *et al.*, 2003). When these crops are grown with lentil and chickpea stubble, 10–15 kg N ha^{-1} less N is needed. Staggenborg *et al.* (2003) reported that wheat following grain sorghum required 21 kg ha^{-1} more N to maximize grain yields compared to wheat planted after soybean. These authors also reported that these previous crop effects were attributed to grain sorghum producing higher levels of residue and that this residue immobilized greater amounts of available N than soybean residue.

Nitrogen supply has been considered to be the main benefits of legumes grown before cereal crops in rotation. The quantity of N availability reported in the literature has varied considerably. For example, Ding *et al.* (1998) reported that soybean supplied 30 kg N ha^{-1} to a following corn crop in Ontario, Canada, while Varvel and Wilhelm (2003) reported that corn obtained 65 kg N ha^{-1} in a two-year rotation with soybean in Nebraska. These latter authors also reported that soybean supplied 80 kg N ha^{-1} to sorghum in a soybean-sorghum rotation. Pedersen and Lauer (2002) reported that corn rotated annually with soybean and first-year corn after five years of consecutive soybean yielded 12% more than continuously grown corn. Supply of N by soybean to the succeeding corn may have been the main factors responsible for these yield increases. Jeranyama *et al.* (2000) reported that legumes cowpea (*Vigna unguiculata* L.) and sunnhemp (*Crotolaria juncea* L.) reduced fertilizer N needs of subsequent corn crops by 36 kg N ha^{-1}. These authors also reported that intercropped annual legumes and small amounts of inorganic fertilizer offer a strategy to meet the N needs of plants grown on smallholder farms in Zimbabwe.

2. Crop Residue Management

Crop residues are portions of plants remaining after seed harvest, mainly by grain crop residues such as corn stover or small grain straw and stubble (Crop Science Society of America, 1992). Residues are important in nutrient

distribution and plant growth (White, 1984), and they affect the amount of soil nutrients available to crops (Dalal, 1989; Mehdi *et al.*, 1999). Plant residues influence N cycling in soils because they are primary sources and sinks for C and N (Dinnes *et al.*, 2002). Residues allow N to be available to plants for longer periods of time through initially immobilizing, and then gradually mineralizing N (Aulakh *et al.*, 1991; Maskina *et al.*, 1993; McKenney *et al.*, 1995). Burgess *et al.* (2002) reported that grain corn residues can supply 40–80 kg N ha^{-1} depending on yield and N concentration, and significantly contributes to soil N pools and soil humas formation.

Incorporation of crop residues into soil provides substantial amounts of nutrients, including N for succeeding crops (Ambus and Jensen, 2001; Carranca *et al.*, 1999). In the long term, straw incorporation has resulted in increased N mineralization potential in rice and non-rice systems (Bacon, 1990). Sustained increases in microbial biomass have been observed following many seasons of straw incorporation compared with burning (Bird *et al.*, 2001; Powlson *et al.*, 1987).

When plant residues having C/N ratios greater than 20/1 are incorporated into soil, available N is immobilized during the first few weeks by the decomposing microbial populations present (Doran and Smith, 1991; Green and Blackmer, 1995; Somda *et al.*, 1991). However, some workers have reported that net immobilization is likely to occur following addition of plant material with C/N ratios above ~25:1 (Brady and Weil, 2002; Burgess *et al.*, 2002). Cereal straws (rice, corn, wheat, and barley) usually have high C/N ratios (Table XIII), and may induce temporary N deficiency in crops due to N immobilization by soil microbial populations when straw is not incorporated or decomposed in advance. However, this temporary adverse effect of N immobilization can be alleviated by applications of about 15 kg N ha^{-1} under most cropping systems (Christensen, 1986).

Legume crop residues are effective sources of N (Bremer and van Kessel, 1992; Haynes *et al.*, 1993). When released in synchrony with crop N demand, crop residue N is a particularly desirable source of N as losses to the environment are minimized (Stute and Posner, 1995; Soon *et al.*, 2001). Legumes residues generally have high N contents and lower C/N ratios compared with cereals (Table XIII). During the mineralization of leguminous materials, up to 50% of the amount of N can be released within two months of incorporation into soil (Kirchmann and Bergqvist, 1989).

Besides providing N, crop residues can provide effective weed control and consequently improve NUE if managed properly. Winter weed residues reduced weed seedling emergence by 45% (Crutchfield *et al.*, 1986) and biomass by 60% in corn (Wicks *et al.*, 1994). Crop residues suppress weed emergence by reducing light penetration and soil temperature fluctuations (Teasdale and Mohler, 1993).

Table XIII
C/N Ratio of Straw of Major Cereal and Legume Crops

Crop species	Growth stage/age in days	C/N ratio	Reference
Corn residues (*Zea mays* L.)	Physiol. maturity	67	Burgess *et al.* (2002)
Rice straw (*Oryza sativa* L.)	Physiol. maturity	69	Eagle *et al.* (2001)
Rice straw (*Oryza sativa* L.)	Physiol. maturity	56	Davelouis *et al.* (1991)
Sorghum (*Sorghum bicolor* L. Moench)	Vegetative	22.0	Clement *et al.* (1998)
Barley straw (*Hordeum vulgare* L.)	Physiol. maturity	99.1	Larney and Janzen (1996)
Ryegrass (*Lolium multiflorum* Lam)	Vegetative	30	Kuo and Jellum (2002)
Rye (*Secale cereale* L.)	Heading	40	Rannells and Wagger (1996)
Alfalfa hay (*Medicado sativa* L.)	Not given	15.9	Larney and Janzen (1996)
Pea straw (*Pisum sativum* L.)	Physiol. maturity	21	Fauci and Dick (1994)
Pea hay (*Pisum sativum* L.)	Not given	15.4	Larney and Janzen (1996)
Red clover (*Trifolium pratense* L.)	101 days	13.7	Kirchmann (1988)
White clover (*Trifolium repens* L.)	101 days	10.7	Kirchmann (1988)
Yellow trefoil (*Medicago lupulina* L.)	101 days	10.1	Kirchmann (1988)
Persian clover (*Trifolium resupinatum* L.)	101 days	15.8	Kirchmann (1988)
Egyptian clover (*Trifolium alexandrium* L.)	101 days	16.7	Kirchmann (1988)
Subterranean clover (*T. Subterraneum* L.)	101 days	11.4	Kirchmann (1988)
Cowpea (*Vigna unguiculata* L. Walp.)	Green pods	13.9	Clement *et al.* (1998)
Sunnhemp (*Crotalaria juncea* L.)	Mature pods	20.2	Clement *et al.* (1998)
Soybean (*Glycine max* L. Merr.)	Vegetative	17.9	Clement *et al.* (1998)
Pigeon pea (*Cajanus cajan* L. Millspaugh)	Not given	25.9	Clement *et al.* (1998)
Wild indigo (*Indigofera tinctoria* L.)	Flowering	15.8	Clement *et al.* (1998)
Sesbania (*Sesbania rostrata* Bremek & Oberm)	Vegetative	27.8	Clement *et al.* (1998)
Sesbania (*Sesbania emerus* Aubl. Urb.)	Vegetative	26.5	Clement *et al.* (1998)
Aeschynomene afraspera	Vegetative	23.9	Clement *et al.* (1998)
Desmanthus virgatus	Green pods	18.9	Clement *et al.* (1998)
Tropical kudzu (*Pueraria phaseoloides*)	Not given	19	Davelouis *et al.* (1991)
Hairy vetch (*Vicia villosa* Roth)	Vegetative	12	Kuo and Jellum (2002)
Hairy vetch (*Vicia villosa* Roth)	Flowering	18	Sainju *et al.* (2002)
Hairy vetch (*Vicia villosa* Roth)	Early bloom	17	Rannells and Wagger (1996)
Crimson clover (*Trifolium incarnatum* L.)	Midbloom	11	Rannells and Wagger (1996)

3. Green Manuring

Green manure is defined as plant material incorporated into soil while green or at maturity. Soil improvement and green manure cropping is any crop grown for the purpose of being turned under while green or soon after maturity for soil improvement (Soil Science Society of America, 1997). Green manure crops can be leguminous as well as nonleguminous, and can be grown *in situ* or brought from outside as cuttings of trees and shrubs. The latter practice is called green leaf manuring (Singh *et al*., 1991). The term *green fallow* has been coined to describe green-manure farming systems that are typically used as partial fallow replacement in wheat-fallow rotations (Pikul *et al*., 1997). In this kind of system, legumes are seeded early in the fallow year, grown to about full bloom, and killed by chemicals or tillage. An important aspect of the green-fallow system is to balance water use for N_2-fixation with water and N requirements of subsequent wheat crops (Pikul *et al*., 1997).

A vast array of legume species have potential as green manures. Several hundred species of tropical legumes may be used, but only a fraction of these have been studied for their potential as green manures. In temperate regions also, numerous legume crops can be used as green manure crops. Annual dry matter accumulation by legumes varies from 1 to over 10 Mg ha^{-1} under ideal growing conditions (Lathwell, 1990). Quantities of N accumulated in the aboveground dry matter range from 20 kg ha^{-1} to as much as 300 kg ha^{-1} (Lathwell, 1990). Research on the Canadian prairies has shown that annual legumes have potential as green manure crops (Rice *et al*., 1993). In grain lentil-wheat (*Lens culinaris* Medikus-*Triticum aestivum* L.) rotations, a gradual reduction in fertilizer N requirement has been reported (Campbell *et al*., 1992). For example, corn grain yields were consistently highest following red clover and often the lowest following annual ryegrass (Vyn *et al*., 1999).

Legumes are superior green manure crops compared with nonleguminous crops because legumes fix atmospheric N (Vyn *et al*., 1999). Considerable variations in N fixation can occur, even among legume species (Hesterman *et al*., 1992). For green manure crops to be agronomically attractive and economically viable, the plants should have some important characteristics: These properties are: They need to be fast growing for easy adjustment into cropping systems; they need to produce sufficient dry matter to ameliorate soil physical, chemical, and biological properties; they need to fix adequate N; and they need to require minimum cultural practices during the growth period so that they are relatively economical to produce.

Beneficial effects of green manure on succeeding crops depend largely on residue quantity and quality, soil type, soil fertility, soil acidity, biological activity, soil moisture, and temperature (Mary and Recous, 1994; Thonnissen

et al., 2000). Ladd *et al.* (1983) and Harris *et al.* (1994) reported that less than 30% of legume N was recovered by subsequent nonlegume crops, and large amounts of legume N were retained in soil mostly in organic forms.

4. Use of Cover Crops

Cover crops are close-growing plants that provide soil protection and soil improvement between periods of normal crop production (Soil Science Society of America, 1997). Cover crops are generally dried by killing them with appropriate herbicides before planting subsequent crops. When plowed under and incorporated into soil, cover crops may be referred to as green manure crops. One potential of cover crop use is a green manure crop replacing fallow periods (Pikul *et al.*, 1997; Schlegel and Havlin, 1997). Cover crops have special importance for reducing NO_3-N leaching during fallow periods when precipitation is high (Kowalenko, 1987). Meisinger *et al.* (1991) reported that cover crops reduced both the mass of N leached and the amount of NO_3-N concentrations in leachates by 20–80% compared to no cover crop. Cover crops improve soil quality, reduce soil erosion, and improve crop yields (Dabney, 1998; Kaspar *et al.*, 2001; Stute and Posner, 1995). Cover crops may also be beneficial for disease, insect, and weed management to decrease need for pesticides (Buhler *et al.*, 1998; Fisk *et al.*, 2001; Vandermeer, 1989). Legume cover crops can replace fertilizer N (Blevins *et al.*, 1990; Hesterman *et al.*, 1992) and maintain soil organic matter and improve soil structure (Reicosky and Forcella, 1998; Smith *et al.*, 1987). These positive effects of cover crops may improve NUE of succeeding crops. Legumes are desirable cover crops because they fix atmospheric N and make N available to succeeding crops (Biederbeck *et al.*, 1996; McGuire *et al.*, 1998; Wallgren and Linden, 1991). Numerous legumes including alfalfa (*Medicago sativa* L.) (Badaruddin and Meyer, 1990; Rice *et al.*, 1993), faba bean, field pea (Biederbeck *et al.*, 1993; Blackshaw *et al.*, 2001; Brandt, 1996; Wallgren and Linden, 1991), lentil (Biederbeck *et al.*, 1993; Brandt, 1996; Pikul *et al.*, 1997), red clover (*Trifolium pratense* L.) (Badaruddin and Meyer, 1990; Schlegel and Havlin, 1997), sweet clover (*Melilotus officinalis* L. Lam) (Blackshaw *et al.*, 2001; Sparrow *et al.*, 1993), and tangier flatpea (*Lathyrus tingitanus* L.) (Biederbeck *et al.*, 1993; Rice *et al.*, 1993) have been used as partial fallow replacement with varying degrees of success. Winter annual legumes such as hairy vetch (*Vicia villosa* Roth) can fix most or the entire N required for maximum corn yields (Clark *et al.*, 1995; Decker *et al.*, 1994; Holderbaum *et al.*, 1990).

Cover crops can accumulate substantial amounts of biomass and potentially available organic N (Vyn *et al.*, 2000). However, the full benefit of using cover crops will be dependent on the synchrony between cover crop N

mineralization and N demand of the subsequent crop as well as an accurate estimation of supplemental fertilizer N requirements of the subsequent crop (Vyn *et al.*, 2000). Legume cover crops, such as hairy vetch, can supply most of the N required for maximum corn yields (Clark *et al.*, 1995,1997; McVay *et al.*, 1989). Because of its high N concentration and low C/N ratio, hairy vetch residues can decompose rapidly in soil (Kuo and Jellum, 2002), and allow for synchrony of N release from residues with corn N demand (Stute and Posner, 1995). Further, hairy vetch can reduce erosion, reduce NO_3-N leaching, and increase organic matter (Sainju and Singh, 1997; Sainju and Singh, 2001).

Cover crops also have potential to suppress weeds (Derksen *et al.*, 2002), and help in improving NUE. Excellent weed suppression has been reported by sweet clover (Moyer *et al.*, 1977). Similarly, weed suppressant of perennial alfalfa (*Medicago sativa* L.) has been reported for three years for wild oat (*Avena fatua* L.) and some other weed species (Entz *et al.*, 1995; Ominski *et al.*, 1999). Weed suppressant effects of cover crops were increased two-fold when combined with no-till compared with reduced-till systems (Anderson, 1999).

In selecting cover crops, legumes are preferred for use because they tend to scavenge residual NO_3-N as well as fix atmospheric N. However, some nonlegume crops have been reported to be better for scavenging residual NO_3-N compared to legumes (Sainju and Singh, 1997; Sainju *et al.*, 1998). McCracken *et al.* (1994) reported that rye reduced NO_3-N leaching by 94%, compared with 48% for hairy vetch. Similarly, Sainju *et al.* (1998) reported that rye had greater root density and aboveground biomass, and scavenged more soil NO_3-N early in the growing season compared to the legumes hairy vetch or crimson clover (*Trifolium incarnatum* L.). Under these situations, a hairy vetch-cereal rye cover crop may be a viable alternative for scavenging residual N and adding fixed atmospheric N_2 in crop production systems (Clark *et al.*, 1997).

5. Use of Nitrogen Efficient Species/Genotypes

Utilization of plant species or genotypes of same species efficient in absorption and utilization of N is an important strategy in improving NUE and sustainable agricultural systems. Differences in N uptake and utilization among crop species and cultivars within species for wheat, sorghum, corn, ryegrass, and soybean have been reported (Moll and Kamprath, 1977; Pollmer *et al.*, 1979; Reed *et al.*, 1980; Traore and Maranville, 1999). Similarly, many researchers have found significant variations of NUE among lowland rice genotypes (Broadbent *et al.*, 1987; Fageria and Baligar, 2003b; Fageria and Barbosa Filho, 2001; Singh *et al.*, 1998). Pandey *et al.* (2001)

reported that agronomic efficiency of N was higher in sorghum compared to pearl millet and corn over four N rates (45, 90, 235, and 180 kg N ha^{-1}). Fowler (2003) reported significant yield differences among wheat genotypes with increasing N rates from 0 to 240 kg ha^{-1}.

Isfan (1993) reported highly significant variation among oat genotypes in both yield and physiological efficiency of absorbed N. According to this author, ideal genotypes could be those that absorb relatively high amounts of N from soil and fertilizers, produce high grain yields per unit of absorbed N, and store relatively little N in the straw. Similarly, many workers found corn genotype differences for absorption and utilization of N (Anderson *et al.*, 1984; Kamprath *et al.*, 1982; Moll *et al.*, 1982, 1987). Lynch and White (1992), and Lynch and Rodriguez (1994) reported genetic variability in NUE of dry bean genotypes.

Figure 11 shows responses of four lowland rice genotypes to N fertilization. These genotypes differ in yield response to applied N and can be grouped into three classes according to their responses to N fertilization. The first group was efficient and responsive to N. The genotype that produced above average yields compared to all the genotypes tested at the low N level responded well to applied N. The genotype CNAi 9018 fell into this group. The second classification was efficient and nonresponsive. The genotype that produced well at low N rates did not respond well at higher N rates. The genotype CNAi 8569 fell into this group. The third group was

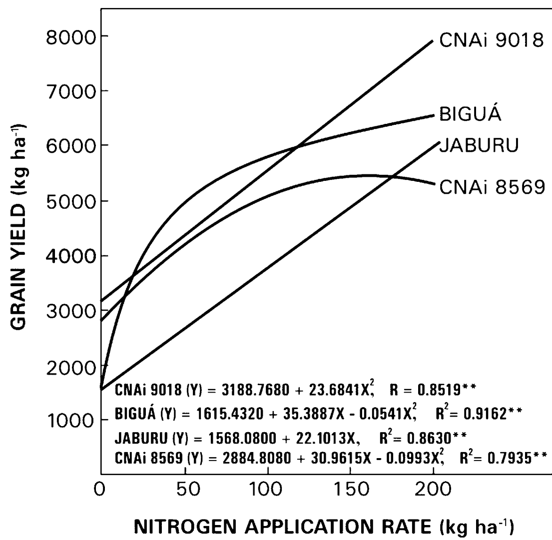


Figure 11 Response of lowland rice genotypes to N fertilization (Fageria *et al.*, 2003b).

genotypes that produced low at low N rates, but responded well to higher N rates. These have been designated as inefficient and responsive. The genotypes Bigua and Jaburu fell into this group. From a practical point of view, the genotypes that fell into the efficient and responsive group would be the most desirable because they can produce well at low soil N levels and also respond well to applied N. Thus, this group could be utilized with low as well as high input technology with reasonably good yields. The second most desirable group would be efficient nonresponsive. Genotypes of this type can be planted under low N level and still produce more than average yields. The inefficient responsive genotypes could be used in breeding programs for their N-responsive characteristics.

Several reasons have been cited as to why some genotypes are more efficient in N utilization compared to others (Thomason *et al.*, 2002). Moll *et al.* (1982) reported that NUE differences among corn hybrids were due to differing utilization of N already accumulated in the plant prior to anthesis, especially at low N levels. Eghball and Maranville (1991) reported that NUE generally parallels water-use efficiency in corn. Hence, both N-use and water-use efficiency traits might be selected simultaneously where such parallels exist. Kanampiu *et al.* (1997) reported that wheat cultivars with higher grain harvest indexes had higher NUEs. Cox *et al.* (1985) reported that wheat cultivars that accumulate large amounts of N early in the growing season do not necessarily have high N-use efficiency. Plants must convert this accumulated N to grain N and must assimilate N after anthesis to produce high NUE. Forms of N uptake (NH_4^+ vs. NO_3^-) may also have effects on NUE (Thomason *et al.*, 2002). Plants with preferential uptake of NH_4^+ during grain fill may provide increased NUE over plants without this preference (Tsai *et al.*, 1992). Ammonium-N supplied to high yielding corn genotypes increased yield over plants supplied with NO_3^- during critical ear development (Pan *et al.*, 1984). Salsac *et al.* (1987) reported that NH_4^+ assimilation processes require 5 ATP (adenosine triphosphate) mol^{-1} of NH_4^+, whereas, NO_3^- assimilation processes require 20 ATP mol^{-1} NO_3^-. This energy saving mechanism may be responsible for higher NUE in NH_4^+-N.

In addition to the previously mentioned reasons, Table XIV summarizes various soil and plant mechanisms and processes and other factors that influence genotypic differences in plant nutrient efficiency. No attempt has been made to discuss these mechanisms or processes in details. For extensive reviews related to nutrient flux and mechanisms of uptake and utilization in soil-plant systems, see Mengal and Kirkby (1982), Barber (1995), Marschner (1995), Fageria *et al.* (1997a), and Baligar *et al.* (2001).

Regarding genotypic variability for N-use efficiency, Rosielle and Hamblin (1981) reported that heritability for grain yield is usually lower for plants grown under low versus high N. Thus, potential progress would be lower for plants grown with low N compared to high N target environments.

Table XIV
Soil and Plant Mechanisms and Processes and Other Factors Influencing Genotypic Differences in Nutrient Use Efficiency in Plants

Nutrient acquisition

Diffusion and mass flow in soil: buffer capacity, ionic concentration and properties, tortuosity, moisture, bulk density, temperature

Root morphological factors: number, length, extension, density, root hair density

Physiological: root/shoot ratio, root microorganisms (rhizobia, azotobacter, mycorrhizae), nutrient status, water uptake, nutrient influx and efflux, nutrient transport rates, affinity for uptake (*Km*), threshold concentration (*Cmin*)

Biochemical: enzyme secretion (phosphatases), chelating compounds, phytosiderophores, proton exudates, organic acid exudates (citric, malic, trans-aconitic)

Nutrient movement in root

Transfer across endoderma cells and transport in roots

Compartmentalization/binding within roots

Rate of nutrient release to xylem

Nutrient accumulation and remobilization in shoot

Demand at cellular level and storage in vacuoles

Retransport from older to younger leaves and from vegetative to reproductive tissues

Rate of chelation in xylem transport

Nutrient utilization and growth

Nutrient metabolism at reduced tissue concentrations

Lower element concentrations in supporting structure, particularly stems

Elemental substitution (Fe for Mn, Mo for P, Co for Ni)

Biochemical: peroxidase for Fe efficiency, ascorbic acid oxidase for Cu, carbonic anhydrase for Zn, metallothionein for metal toxicities

Other factors

Soil factors

Soil solution: ionic equilibria, solubility, precipitation, competing ions, organic ions, pH, phytotoxic ions

Physiochemical properties: organic matter, pH, aeration, structure, texture, compaction, moisture

Environmental effects

Intensity and quality of light (solar radiation)

Temperature

Moisture (rainfall, humidity, drought)

Plant diseases, insects, and allelopathy

Sources: Baligar *et al.* (2001); Fageria and Baligar (2003b); Fageria *et al.* (1997a).

Banziger and Lafitte (1997a) reported that heritability of grain yield usually decreases for plants grown under low N. Banziger and Lafitte (1997b) reported that secondary traits (ears per plant, leaf senescence, and leaf chlorophyll concentration) are valuable for increasing the efficiency of selection for grain yield when broad-sense heritability of grain yield is low under low N environments.

6. Control of Diseases, Insects, and Weeds

Diseases, insects, and weeds are the most yield-limiting factors for most crop plants grown under most agroecological regions. It has been reported worldwide that annually, pests destroy about 35% of all potential crops before harvest (Albert *et al.*, 1992). Approximately 12% of potential crop losses have been attributed to arthropods (Pimentel, 1986). Control or keeping at threshold levels of these yield-limiting factors can improve NUE and consequently higher crop yields. The practices adopted for control of pests may vary from crop to crop, region to region, and socioeconomic conditions of farmers. In modern agriculture, one of the best approaches to reduce risk of pests is using resistant crop species or genotypes within species. This practice not only reduces costs of production, but also reduces environmental pollution. However, resistant cultivars to many pest stresses are not available and pest control methods may not be at sufficient or desirable levels. Hence, a combination of genetic and chemical control is a desirable strategy.

Supply of N in adequate amounts along with proper balances of other essential nutrients, especially P and K, can reduce plant stresses, improve physiological resistance, and decrease disease risk (Krupinsky *et al.*, 2002). It has been reported that wheat fields receiving or with low N rates often have higher levels of tan spot (*Pyr. tritici-repentis*) disease than adequately fertilized fields (Fernandez *et al.*, 1998).

E. Improving Biological and Non-Biological Nitrogen Fixation

Biological N fixation (N_2) by legumes is a spectacular biological phenomenon in nature and its importance for adding N to agricultural systems is enormous. This process may be considered similar to photosynthesis in green plants. Photosynthesis is the basis for all crop yields. Similarly, the contribution of biological N fixation to reducing costs of crop production and maintaining healthy soil quality is of paramount importance. Farming systems based on legumes maintain productivity of the land for many generations (Papastylianou, 1999). More than 60% of the N inputs to natural plant communities have a biological origin (Postgate and Hills, 1979). Quantity of N_2 fixed by crop species varies according to soil-plant environmental factors. Larue and Patterson (1981) reported that on average legumes fix 70 kg N year^{-1} ha^{-1}. No doubt, better crop management practices are desired to improve efficiency of cropping systems. For example, soil acidity significantly influences biological nitrogen fixation by crop plants (Correa *et al.*, 2001). Hence, improving soil pH or reducing soil acidity through liming can improve N_2 fixation significantly. Crop species have optimal soil pH values

for biological activities (Adams, 1981). The optimal soil pH values should be used with caution because optimal pH will vary with soil type and among cultivars of the same species (Fageria *et al.*, 1997a). Furthermore, numbers of *Rhizobia* species capable of nodulating alfalfa, white clover, and soybean were found to increase following application of biosolids (sewage sludge) to soil (Angle, 1998). This was observed despite the fact that the metal content of the soil was sufficiently high to produce visible signs of toxicity in the respective macrosymbiont (Angle, 1998). Genetic variability in N_2-fixation sensitivity to water deficit among soybean cultivars has been reported (Sall and Sinclair, 1991; Serraj and Sinclair, 1997). Hence, planting drought-tolerant genotypes can improve N_2-fixation under low moisture conditions.

Free-living microorganisms or organisms not directly associated with higher plants are capable of non-symbiotic N fixation (Stevenson, 1982). Many heterotrophic bacteria are capable of fixing N including *Beijerinckia* and *Azotobacter*, which are aerobes and found in tropical and temperate soils, respectively (Davis *et al.*, 2003). *Clostridium* is a heterotrophic bacterium that thrives only under anaerobic conditions. *Azospirillum* is a bacterium that has been found to live in the rhizosphere of tropical grass roots. Certain photosynthetic bacteria and cyanobacteria (blue green alga) live near the soil surface and can fix N non-symbiotically (Davis *et al.*, 2003).

Cyanobacteria contribute N to flooded rice by reducing N_2 to NH_3 (Kamuru *et al.*, 1998). Improving mutant strains of cyanobacteria can potentially contribute more N to growth and yield of rice plants than wild types. Several mutant N_2-fixing procaryotes with the ability to excrete NH_3 have been produced, including mutants of *Klebsiella pneumoniae* (Shanmugam and Valentine, 1975), *Nostoc muscorum* (Singh *et al.*, 1983), and *Azotobacter* species (Terzaghi, 1980). Spiller *et al.* (1986) produced a nitrogenase-derepressed mutant strain of the cyanobacterium *Anabaena variabilis* (strain SA-1) that is capable of excreting NH_3 produced by nitrogenase. Kamuru *et al.* (1998) reported that the contribution of the mutant *Anabaena variabilis* (strain SA-1) to growth and yield of rice was equivalent to the application of 71–73 kg N ha^{-1} as $(NH_4)_2SO_4$.

For heterotrophic N-fixing microorganisms, organic C is required as an energy source. The effect of organic matter on soil microbial activity depends on the type of material, its nutrient content, and the initial soil fertility (Jurgensen, 1973). When organic materials such as sugars or straw are added to soil, N fixation can increase (Davis *et al.*, 2003). However, higher concentrations of inorganic N (NO_3^- >35–40 kg ha^{-1}) can inhibit N_2 fixation and even reduce populations of these microorganisms (DeLuca *et al.*, 1995). Activities of free-living microorganisms can be increased by maintaining soil moisture at field capacity (Roper, 1983). Similarly, liming acidic soils has stimulated both *Azotobacter and Beijerinckia,* and increased N_2 fixation (Jurgensen, 1973*). Azotobacter* is relatively tolerant to high pH levels and

Beijerinckia tolerates pH as low as 5.0–5.5. It is generally accepted that the contribution of the nonsymbiotic N-fixing microorganisms to arable soils is small. For upland soils where wheat is grown, non-symbiotic N_2 fixation can approach 5 kg N ha^{-1} yr^{-1} (Steyn, 1970).

Several methods for calculating the N_2 fixed by legumes have been proposed (Papastylianou, 1999). The most widely used methods are the difference method, N accumulation, the acetylene reduction technique, and ^{15}N methodology. A detailed discussion of these methods is provided by Larue and Patterson (1981) and Danso (1995).

VIII. CONCLUSIONS

Efficient nutrient management is essential in modern crop production systems by providing a balance between nutrient inputs and outputs over the long term. The nutrient balancing strategy will improve crop yields as well as NUE, and also help in avoiding soil depletion. In modern agriculture, N is the key nutrient limiting yields of most crops grown in most agroecological regions. The higher N requirements of modern crop cultivars are associated with their higher radiation use efficiencies and consequently higher yields. Recovery of N by crops grown under most cropping systems is less than 50%. This low recovery is associated with N losses from NO_3–N leaching, NH_3 volatilization, surface runoff, and denitrification.

The major uptake forms of N are NH_4^+ and NO_3^- by crop plants. Both forms are equally effective in uptake processes. However, quantity of N form in the soil during uptake determines which form plants prefer. The predominant form of available N in most soils is NO_3^--N. In general, uptake of NO_3^- requires about five times more energy compared to NH_4^+. Efficiency of N in plants is associated with quantity absorbed as well as utilized in the formation of grain. Hence, partitioning of N in vegetative parts and grain is fundamental for higher yields. The N uptake in grain is normally associated with significant quadratic relationships with grain yield. Similarly, NUE in plants also has positive associations with grain yield. The N partitioning and use efficiency varies with crop species and cultivars within species. Hence, planting N-efficient genotypes is a very attractive strategy for reducing costs of crop production, improving crop yields, and keeping a healthy environment. Shoot dry weight, GHI, and NHI are important determinants of grain yield and these traits are significantly influenced by N fertilization.

Adopting improved crop management practices can increase NUE in crops. These improved practices include creating favorable environmental conditions for crops, which lead to higher N uptake and utilization, and consequently higher yields. Management practices such as adequate rates,

appropriate sources, efficient methods of application, and application timing when crops absorb maximum amounts are important N management strategies. Nitrogen is a mobile nutrient in soil-plant systems. Nitrogen recommendations based on field trials that determine crop responses to various rates of fertilizer application are highly efficient and effective. Plant tissue tests compared with specified benchmark concentrations that separate deficient, sufficient, or toxic levels are an important diagnostic method of plant N status. Further, use of appropriate crop rotations, conservation tillage systems, use of organic manures, and improving biological N fixation systems enhance crop productivity. Control of insects, diseases, and weeds are important crop management strategies, which further improve NUE. Better understanding of N interactions with other nutrients may be useful in understanding the importance of balanced supplies of nutrients, and consequently improvement in plant growth or yields. Hence, higher NUE can be achieved.

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FORAGE CHICORY (*CICHORIUM INTYBUS* L.): A REVIEW OF ITS AGRONOMY AND ANIMAL PRODUCTION

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Chicory (*Cichorium intybus* L.) is a perennial herb that has been used as a forage for livestock in many parts of the world. Forage chicory produces a large quantity of high quality feed in the warm season under favorable conditions. Animal performance on chicory is similar to that on legumes and superior to grass-based pastures. In addition, grazing chicory can decrease some internal parasites in livestock, and therefore has potential to reduce the use of anthelmintics. Being a deep-rooted perennial herb, chicory can reduce nitrate leaching, deep drainage, thereby reducing the rate of soil acidification and the occurrence of dryland salinity. This paper reviews the published research work on the agronomic characteristics, herbage production, grazing management, persistence under grazing, nutritive value, and animal performance of forage chicory, as well as the problems encountered when incorporating chicory into farming systems.

I. INTRODUCTION

Chicory (*Cichorium intybus* L.) is a component of natural grasslands in many parts of the world and has been for thousands of years but has only a relatively recent history as a forage crop and as a component of perennial pastures. "Grasslands Puna" chicory (Puna chicory hereafter) was the world's first forage cultivar of chicory when released in New Zealand in 1985 (Rumball, 1986), but further cultivars are now regularly released. Puna chicory has been widely adopted in many parts of the world (Barry, 1998; Jones and Haggar, 1994). Puna chicory has high production (Belesky *et al.*, 1999; Hare *et al.*, 1987; Lancashire, 1978), high feed quality (Barry, 1998; Clark *et al.*, 1990a), and high mineral content (Foster, 1988; Hoskin *et al.*, 1995), and has produced high growth rates in lambs, deer, and cattle. Puna chicory has higher organic matter (OM) digestibility and voluntary feed intake (VFI) than grass-based pastures during spring, summer, and autumn (Kusmartono *et al.*, 1996a; Niezen *et al.*, 1993a), resulting in greater sheep, cattle, and deer production in terms of liveweight gain (Fraser *et al.*, 1988; Hoskin *et al.*, 1995, Niezen *et al.*, 1993a; Scales *et al.*, 1994), carcass weight (Min *et al.*, 1997), and velvet antler production (Kusmartono *et al.*, 1996a). In addition, Puna chicory does not cause bloat when fed to cattle (Barry, 1998), and has reduced the effects of internal parasites in sheep compared with grasses (Scales *et al.*, 1994).

Chicory has some agronomic shortcomings. Rapid reproductive stem growth in spring (Clark *et al.*, 1990b; Hare *et al.*, 1987; Li *et al.*, 1997a) that requires specific management and limited persistence of 3–7 years (Hume *et al.*, 1995; Li *et al.*, 1997b) has slowed its adoption in some farming

systems. The winter dormancy of chicory (Rumball, 1986) results in difficulty in selecting companion species (Hare *et al.*, 1987; Kemp *et al.*, 2002) to balance feed supply all year round (Belesky *et al.*, 2000; Hume *et al.*, 1995). This paper reviews the published research work on the agronomic characteristics, herbage production, grazing management, persistence under grazing, nutritive value, and animal performance of forage chicory as well as the problems encountered when incorporating chicory into farming systems.

II. HISTORY AND BREEDING

Chicory (*Cichorium intybus* L.) is a perennial herb of the family *Asteraceae*, native to Europe, many parts of Asia, Africa, and America (Clapham *et al.*, 1962). Chicory is grown as a leaf vegetable "witloof," or salad green in Europe (George, 1985; Schoofs and de Langhe, 1988), as a fructose crop in many parts of the world (Chubey and Dorrell, 1977; Meijer and Mathijssen, 1992; Pollock and Chatterton, 1988), and its roots are often used as a coffee substitute (Taylor, 1981), or supplement, particularly in India (Arya and Saini, 1984) and South Africa, where more than 90% of all coffee consumed once contained chicory (Anonymous, 1978). In agriculture, chicory was once considered a weed because it was commonly found along roadsides and in waste areas, and was especially common in areas of former cultivation. It can be a troublesome weed in crops. In Canada, naturalized chicory is adapted to the conditions of Atlantic Canada and grows wild throughout the region (Kunelius and McRae, 1999). In Pennsylvania, chicory was listed as a noxious weed until 1993 when the Department of Agriculture Pennsylvania made an exception to allow its use as a forage crop (Jung *et al.*, 1996).

Elliott (1902, cited by Foster, 1988) was the pioneer of chicory use in pasture in the United Kingdom, but the first person to introduce chicory into Britain was Arthur Young from France in 1785. However, it was Elliot who did some scientific work on chicory (Foster, 1988). In New Zealand, chicory was first recorded in 1867 (Hooker, 1867) and was commonly found on roadsides and wastelands of both Islands (Cheeseman, 1906). It was often included in grass-seed mixtures (Anonymous, 1918), but the growth of chicory was insufficient to make a significant contribution to pasture productivity and the plant quickly developed seed heads (Cockayne, 1915). Cockayne (1915) classed chicory as a weed in pasture. O'Brien (1955) also concluded that chicory had poor persistence and had little value as a forage plant, but had a good growth potential on low fertility soil that dried out in summer (O'Brien, 1955).

Chicory was re-evaluated as a potential forage species in the mid-1970s in New Zealand. After over 10 years of selection, a cultivar "Grasslands Puna"

was approved in 1984 and became commercially available in 1985 as the world's first forage cultivar (Rumball, 1986). The use of Puna chicory has now spread throughout New Zealand and the cultivar is also used commercially in Australia, North America, and South America and has been evaluated in parts of Europe and Asia (Barry, 1998). Cultivars currently available in New Zealand include Grasslands Puna, Puna II, Choice, Grouse and Chico. Two forage cultivars, "Lacerta" and "Forage Feast," have subsequently become available in the USA. "Lacerta" is a synthetic variety derived from an ecotype grown by Uruguayan farmers. It is more uniform and has a more erect growth habit, and a lower proportion of plants remain vegetative in the first year compared with Puna chicory (Foster *et al.*, 2002). "Forage Feast" is derived from a specialist group of root chicory varieties used for fructan production and was selected for uniformity in vegetation and time of bolting in France (Foster *et al.*, 2002). Rumball *et al.* (2003a,b) recently released two forage cultivars, "Puna II" and "Choice," that were bred from Grasslands Puna chicory from 1992 to 1998. "Puna II" was selected for tolerance to the fungus *Sclerotinia*, cool-season activity, greater morphological uniformity, and high levels of the sesquiterpene lactones (Rumball *et al.*, 2003a). It is intended for use as a pure sward on non-milking farms, and as a component of mixed swards on all grazing farms. "Choice" was bred with selection emphasis on winter growth, greater morphological uniformity, lower levels of the sesquiterpene lactones (Rumball *et al.*, 2003b). It is intended for use on dairy farms, where the low levels of these compounds would be most unlikely to cause a taint or bitter aftertaste in the milk. New cultivars of chicory continue to be released; however, most of the research on herbage production and animal performance to date has been on Puna chicory.

III. AGRONOMIC CHARACTERISTICS

A. Growth and Development

Puna chicory is active in warm seasons but dormant in winter (Lancashire and Brock, 1983). It is a rosette plant with broad prostrate leaves in winter and more erect leaves in warm seasons. During its first growing season, chicory usually has one intact crown which splits into multi-crowns from its second growing season (Hume *et al.*, 1995; Li *et al.*, 1997a) similar to some tap-rooted legumes, such as alfalfa (*Medicago sativa* L.) (Leach, 1979; Nelson and Smith, 1968). The taproot of chicory can be exposed and damaged by overgrazing and treading (Rumball, 1986).

The fast growth rate of chicory (up to 150 kg DM ha^{-1} day^{-1}) in late spring and early summer is a result of the rapid development of its reproductive

stems (Hare *et al.*, 1987; Matthews *et al.*, 1990). Clapham *et al.* (2001) found that the mean times to initiation of bolting and first open flower were 400 and 1030 growing degree days from calendar day 90 using a base temperature of 5 °C. Puna chicory does not produce seed heads until it is vernalized (George, 1985; Hare *et al.*, 1987). With warm temperature in spring, chicory rapidly produces large numbers of leaves from the crown and from the main reproductive stems, which elongate quickly after bolting is initiated in late spring. Puna chicory starts to flower in late spring and continues until summer, with a peak in late December in New Zealand (Hare *et al.*, 1987). Chicory matures quickly and produces a hollow primary stem in mid-spring that thickens and hardens substantially from a height of approximately 60 cm and continues to grow to over 2 m tall if reproductive growth is not controlled (Barry, 1998; Hare *et al.*, 1987; Rumball, 1986). Defoliation suppresses the development of the primary reproductive stem but stimulates the development of secondary stems. Axillary shoots, however, become reproductive regardless of defoliation management (Li *et al.*, 1998).

Flower buds form in the axils of the upper leaves of the main stem and primary branches. Total flower production averages 227 flowers/plant^{-1} (Clapham *et al.*, 2001). Flowers are cross-pollinated largely by honey bees. Seeds mature 20 days after pollination (Hare, 1986). The 1000-seed weight is 1.3–1.7 g (Hare, 1986), and the seed yield ranges from 200 to 500 kg ha^{-1} (Hare *et al.*, 1990). Where moisture is not limiting, seed yield can increase linearly with increasing rate of applied nitrogen (N) up to 300 kg N ha^{-1} (Rowarth *et al.*, 1996). The increased seed yields from N are due to an increase in stem size and branch number, resulting in more flower sites. Puna chicory appears to be more sensitive to the rate of N than timing of N application, as it is able to compensate between development of stem and branches (Rowarth *et al.*, 1996).

Puna chicory can be sown in either autumn or spring, and establishes rapidly. The sowing rate for chicory has been recommended to be in the range 1.5–3.0 kg ha^{-1} for pure stands and less than 1.5 kg ha^{-1} for binary and complex mixtures with white clover (*Trifolium repens* L.) or winter-active grasses (Arias-Carbajal, 1994). However, in practice farmers usually prefer higher sowing rates of up to 5 kg ha^{-1} ha for forage crops to obtain high initial plant density and good weed suppression. Jung *et al.* (1996) noted that little herbage growth of chicory occurred when the mean temperature was less than 14 °C, so autumn sowings need to be early enough to allow for seedling establishment before winter. Superior seedling vigor was exhibited in spring plantings of chicory and the potential forage mass was 7.5 t ha^{-1} in the sowing year (Jung *et al.*, 1996). Spring-sown crops do not produce seed heads until the next summer (Hare and Rolston, 1987). Clapham *et al.* (2001) observed that about 58% of Puna chicory plants became reproductive each growing season, after the establishment year.

B. Soil Requirements and Fertilizers

Puna chicory grows best on well-drained soils with medium to high fertility (Hare *et al.*, 1987). Like all highly productive forage species, chicory needs a high nutrient input to sustain high production, especially on soils with marginal fertility (Belesky *et al.*, 2001). Standard nutrient requirements of Puna chicory are Olsen phosphorus (P) 20–30 mg kg^{-1}, potassium (K) >8 mg kg^{-1}, and sulfur (S) >10 mg kg^{-1} (Moloney and Milne, 1993). Upjohn *et al.* (2002) recommended that a maintenance rate of 25–40 kg P ha^{-1}, 20 kg K ha^{-1}, and 20 kg S ha^{-1} in early spring would sustain high growth rates of chicory. Moloney and Milne (1993) suggested that 35 kg N ha^{-1}, 35 kg P, and K ha^{-1}, and 20–30 kg S ha^{-1} were required as a maintenance application in August (early spring).

Being a non-legume species, N fertilizer is essential in a pure chicory stand, particularly during seedling development. Moloney and Milne (1993) recommended 35 kg N ha^{-1} in August and 20–25 kg N ha^{-1} in early December. Ameziane *et al.* (1995) found that insufficient N can decease the shoot-root ratio in chicory by decreasing leaf area of shoots, and Ameziane *et al.* (1997) found that low N resulted in a 30–35% decrease in ^{13}C assimilation relative to higher N supply. At 12 days after sowing, shoot-root dry mass ratio in plants grown at low N was less than one-third of that of plants grown at a higher N concentration.

Puna chicory can tolerate a wide range of pH (4.8–6.5) (Barry, 1998), but grows best in the range pH 5.6–6.0 (Crush and Evans, 1990). Upjohn *et al.* (2002) stated that Puna chicory was able to produce high quality forage on acid soils but did not specify pH. Crush and Evans (1990) found that concentrations of zinc (Zn), boron (B), copper (Cu), manganese (Mn), S, and K in chicory decreased significantly, but calcium (Ca) increased as soil pH increased. Chicory is rich in minerals (Crush and Evans, 1990), but where micronutrients such as B are deficient in the soil, fertilizer might be warranted (Belesky *et al.*, 2001).

IV. HERBAGE PRODUCTION

A. Dry Matter Production and Seasonal Distribution

Puna chicory can grow at a rate in excess of 150 kg DM ha^{-1} day^{-1} in favorable conditions (Hare *et al.*, 1987; Matthews *et al.*, 1990). Herbage production of 7–9 t ha^{-1} is very common for pure chicory stands for the first two or three years under grazing conditions (Table I). However, herbage production decreases significantly as plants age. Li *et al.* (1997a) found herbage

Table I
Annual Total Herbage Yield (t DM ha^{-1}) for Pure Puna Chicory Stands

Country	Year 1	Year 2	Year 3	Year 4	References
Palmerston North, NZ[a]	8.5	9.4	-	4.6	Li *et al.* (1997a)
Oklahoma, USA	7.5	7.7			Volesky (1996)
West Virginia, USA	7.8	6.3	7.6		Belesky *et al.* (1999)
Pennsylvania, USA	9.4	7.9			Jung *et al.* (1996)
Prince Edward Island, Atlantic Canada	7.1	5.8	6.4		Kunelius and McRae (1999)
Orange, New South Wales, Australia[b]	2.10	4.3	6.5	9.4	Kemp *et al.* (2002)

[a]Yield from November to April.
[b]Green-leaf dry matter yield, nitrogen fertilizer applied at 100–150 kg ha^{-1} year^{-1} in years 3 and 4.

Table II
Seasonal Distribution (%) of Total Herbage Yield for Puna Chicory

Year	Spring	Summer	Autumn	Winter
Year 1[a]	21	47	32	-
Year 2[a]	37	32	31	-
Year 4[a]	43	33	24	-
Year 1–4[b]	32	49	14	5

[a]Percentages were based on total yield without winter yield from Li (1997).
[b]Four year average in mixed pastures from Hume *et al.* (1995).

production in year 4 was only half of the yield in years 1 and 2. However, Kemp *et al.* (2002) found that Puna chicory can produce 9.4 t ha^{-1} in year 4 with 100–150 kg N fertilizer ha^{-1} year^{-1} and green-leaf yields from chicory were consistently superior to alfalfa and phalaris (*Phalaris aquatica* L.).

Puna chicory displays a distinct seasonal pattern of growth in response to temperature, being virtually dormant in winter and highly active in spring and summer (Table II). In the southern hemisphere, chicory is productive from September to May, but some cultivars are more cool-season active than others, resulting in a longer growing season. Chicory avoids all but the most prolonged summer droughts due to its deep, thick taproot. Drought avoidance and high DM production over summer (Hare *et al.*, 1987; Lancashire, 1978) ensure feed availability when livestock requirements are high (Hunt and Hay, 1990). Kemp *et al.* (2002) observed that Puna chicory was the only pasture species that produced useful quantities of green leaf during the 1990–1991 summer drought in central NSW, Australia. Chicory appeared to have less leaf senescence than alfalfa and phalaris when water stressed.

Table III
Total Annual Pasture Production and Puna Chicory Contribution in Different Chicory-Based Pastures Mixtures

Chicory-based pasture mixtures	Year 1	Year 2	Year 3	Year 4
Perennial ryegrass (*Lolium perenne* L.)-white clover (*Trifolium repens* L.)[a]				
Total green DM (t DM ha^{-1})	16.2	13.5	13.0	12.6
Chicory contribution (%)	22	73	87	63
Perennial ryegrass-cocksfoot (*Dactylis glomerata* L.)-white clover[a]				
Total green DM (t DM ha^{-1})	15.0	11.9	12.7	11.4
Chicory contribution (%)	23	73	76	54
Tall fescue (*Fescue arundinacea* Schreb.)-white clover[a]				
Total green DM (t DM ha^{-1})	15.8	14.1	14.5	12.1
Chicory contribution (%)	59	94	96	69
Prairie grass (*Bromus willdenowii* Kunth.)-white clover[a]				
Total green DM (t DM ha^{-1})	16.5	14.0	13.4	11.1
Chicory contribution (%)	32	92	95	75
Phalaris (*Phalaris aquatica* L.)-white clover[a]				
Total green DM (t DM ha^{-1})	16.0	14.4	15.0	14.0
Chicory contribution (%)	35	69	71	29
Cocksfoot[b]				
Total green DM (t DM ha^{-1})	7.0	6.3	7.2	
Chicory contribution (%)	50	30	19	
Cocksfoot-birdsfoot trefoil (*Lotus corniculatus* L.)[b]				
Total green DM (t DM ha^{-1})	8.0	6.1	6.9	
Chicory contribution (%)	50	28	20	
Birdsfoot trefoil[c]				
Total green DM (t DM ha^{-1})	6.2	6.3	6.6	
Chicory contribution (%)	73	-	63	
Timothy (*Phelum pratense* L.)-alfalfa (*Medicago sativa* L.)[c]				
Total green DM (t DM ha^{-1})	7.2	8.6	8.4	
Chicory contribution (%)	42	-	42	
Timothy (*Phelum pratense* L.)-red clover (*Trifolium pretense* L.)[c]				
Total green DM (t DM ha^{-1})	8.6	7.8	7.7	
Chicory contribution (%)	30	-	25	
Timothy (*Phelum pratense* L.)-white clover[c]				
Total green DM (t DM ha^{-1})	7.2	7.3	8.4	
Chicory contribution (%)	41	-	51	
Meadow bromegrass (*Bromus riparius* Rehm.)-white clover[c]				
Total green DM (t DM ha^{-1})	7.1	6.3	7.6	
Chicory contribution (%)	49	-	38	
Tall fescue-white clover[c]				
Total green DM (t DM ha^{-1})	8.1	6.7	8.1	
Chicory contribution (%)	35	-	47	
Cocksfoot-white clover[c]				
Total green DM (t DM ha^{-1})	7.1	8.4	9.4	
Chicory contribution (%)	24	-	25	

Table III (*continued*)

Chicory-based pasture mixtures	Year 1	Year 2	Year 3	Year 4
Meadow fescue-white clover[c]				
Total green DM (t DM ha^{-1})	7.2	7.4	7.3	
Chicory contribution (%)	34	-	56	
Red fescue (*Fescue rubra*)-meadow fescue (*Fescue pratense*)[d]				
Total green DM (t DM ha^{-1})	8.5	3.9	7.3	
Chicory contribution (%)	36	2	0	

[a]Hume *et al*. (1995) at Manawatu, NZ
[b]Belesky *et al*. (1999) at West Virginia, USA
[c]Kuneliu and McRae (1999) at Prince Edward Island, Atlantic Canada where growing season ranges from 160 to 210 days (>5 °C)
[d]Fisher *et al*. (1996) at Ayr, UK

The seasonal growth pattern of chicory fits the requirements of animals for high feed quality in late spring and summer. For temperate pasture species, the usual pattern is high yield and quality in spring associated with vegetative stages of growth, but poor feed quality and low yield over summer due to plant maturity (Waghorn and Barry, 1987) and moisture stress (Adam, 1988). Thus, inadequate feed quality relative to animal requirement is a limitation to animal production from many pasture species (Christian, 1987) during summer. For example, red deer (*Cervus elaphus*) in New Zealand calve between November and December and are at peak lactation over summer while lambs are usually at post weaning and capable of fast growth in summer (Komolong *et al*., 1992; Niezen *et al*., 1993a).

The vigorous growth and high nutritive value of chicory in mid- to late-summer enables the forage systems in North America to meet the energy and nutrient requirements for livestock, as midseason forage production often lags in cool-temperature-origin pastures and forces producers to determine livestock numbers for their particular operation based on the occurrence of a mid- to late-season forage deficit (Belesky *et al*., 1999; Jung *et al*., 1996; Volesky, 1996). Kunelius and McRae (1999) in Atlantic Canada also suggested that including Puna chicory in grass-legume swards could improve the seasonal distribution of herbage and increase late season herbage production.

Since the release of Puna chicory, researchers from many parts of the world have tried various combinations of perennial grasses and legumes with chicory as listed in Table III. Winter active grasses can compensate for the low growth activity of chicory in the cool season. However, the strong warm season growth of chicory can be detrimental to the growth of the companion grasses or legumes. The ideal companion grass species should not only have complementary seasonal growth to chicory, but also have morphological characteristics that minimize competition between the two species (Hume *et al*., 1995). A suitable legume species would be beneficial to reduce the N

fertilizer input to chicory. Farmer experience in New Zealand has demonstrated that both white clover and red clover (*Trifolium pratense* L.) persist in combination with chicory.

In highly favorable environmental and management conditions in New Zealand, the chicory-based mixed pastures have yielded up to 16 t ha^{-1} with Puna chicory contributing 34, 80, 85, and 57% to the green DM yield for years 1–4, respectively (Hume *et al.*, 1995). In North America, the annual herbage yield in mixed pasture was 6–9 t ha^{-1}, only half of that produced in the more favorable conditions in New Zealand, and the contribution of chicory to the swards was significantly less (Table III). Kunelius and McRae (1999) found that mixtures of cocksfoot (*Dactylis glomerata* L.) + white clover, timothy (*Phleum pratense* L.) + alfalfa, and timothy + red clover in combination with chicory produced the highest dry matter yields, whereas chicory alone or a chicory + birdsfoot trefoil (*Lotus corniculatus* L.) combination had the lowest production in the cold-winter region of Atlantic Canada (Table III). However, the proportion of chicory in the mixtures was least in combination with cocksfoot (23.9–29.5%) and timothy + red clover (25.0–29.5%), and highest when grown alone (68.7–94.5%) or with birdsfoot trefoil (62.5–70.3%).

Seasonal DM yield was highest for chicory + white clover in combination with cocksfoot, timothy + alfalfa, or timothy + red clover, due to the high yield in the first cut (Kunelius and McRae, 1999). Belesky *et al.* (1999) reported that chicory was grown successfully in association with cocksfoot and birdsfoot trefoil under the climatic and edaphic conditions in the central Appalachian region. Jung *et al.* (1996) reported that Puna chicory produced 9.4 t DM ha^{-1} over two years when mixed with "Pennlate" cocksfoot. In contrast, Lancashire and Brock (1983) found that Puna chicory contributed 35% of total yield in the summer of year 1 and only about 10% in the summer of year 3 in a pasture under rotational grazing, whereas Moloney (1992) recorded maximum contents of 6% in summer (3–4% of annual yield) from farm sowings in New Zealand. Fisher *et al.* (1996) found Puna chicory disappeared from year 2 in a mixture of two fescue grasses in United Kingdom (Table III). Martensson *et al.* (1998) examined a number of combinations of grasses, forbs, and clover species under different defoliation managements on sandy loam, or loamy sand soils, and concluded that Puna chicory did not persist, and performed poorly in these mixes. Chicory's failure to contribute in some pasture mixes is most likely due to the dual effects of selective grazing and treading damage during late autumn and winter.

Ruz-Jerez *et al.* (1991) compared three pasture systems in pasture productivity, dynamics of botanic composition, and N flux through the herbage yield at Palmerston North, New Zealand. In the herbal ley pasture, Puna chicory was the main contributor among the herbs and made a substantial

contribution to total yield, followed by white and red clovers. Ruz-Jerez *et al.* (1991) concluded that the performance of the herbal ley offers the promise of an alternative, specialist pasture and would be highly beneficial if quality feed is required.

Overall, phalaris appears to be the most complementary companion grass for Puna chicory. Hume *et al.* (1995) tried mixtures of chicory with phalaris, cocksfoot, and perennial ryegrass (*Lolium perenne* L.) in the North Island of New Zealand and found that the phalaris-chicory combination was best in terms of maximizing total annual yields and spreading production more evenly through the year. Belesky *et al.* (1999) also reported that phalaris-chicory was the best grass-chicory mixture, but the winter production was still not as high as the red clover-ryegrass mixture. Phalaris has a high level of cool-season activity, complementing the low winter productivity of chicory, and summer production of phalaris can be strong as it forms reproductive tillers. The open, rhizomatous, and "mobile" nature of phalaris may have enhanced its compatibility with the upright habit of chicory compared with the densely tillered, tufted growth form of species such as cocksfoot and ryegrass, competing for the same space. However, Kemp *et al.* (2002) found the proportion of phalaris rarely exceeded 10% of the total dry weight when mixed with chicory plants in New South Wales, Australia.

Puna chicory swards can be invaded by volunteer grasses and legumes, with the process accelerated by the decrease in chicory plant density over time, especially at higher N fertilizer rates (Belesky *et al.*, 2000). To mix other species into chicory swards can reduce the invasion of annual weeds. Gaps in pure chicory swards, especially those present after cutting events, provide sites for weed and naturalized plant invasion (Belesky *et al.*, 1999). The sowing of cocksfoot and birdsfoot trefoil with chicory retarded invasions by less desirable species and this offered a means of controlling overall sward productivity and herbage composition (Belesky *et al.*, 1999). Alternatively, white clover can be used to fill gaps in chicory and grasses can be removed with herbicide.

B. Responses to Nitrogen Fertilizer

Chicory needs an external N supply. Collins and McCoy (1997) observed that chicory herbage yield increased linearly with N rates between 0 and 200 kg N ha^{-1}. Collins and McCoy (1997) found that Puna chicory utilized the N applied quickly and efficiently. They estimated that the total recovery of N applied during the entire season was about 80% of N applied (Collins and McCoy, 1997). Belesky *et al.* (2000) found that chicory growth responded to rates up to 480 kg N ha^{-1}. However, high N rates were associated with declining plant density and regrowth (Belesky *et al.*, 2000; Clark *et al.*,

1990a). Increasing N from 0 to 480 kg N ha^{-1} depressed the presence of chicory from 46% to 3.3% for a year 3 chicory pasture in West Virginia (Belesky *et al.*, 2000). Clark *et al.* (1990b) showed that spring response to 1 kg of N was 10.6 kg DM ha^{-1} (rates up to 50 kg ha^{-1}), similar to that of ryegrass and white clover pasture; however, 60% of the response was in stem production. Belesky *et al.* (2000) observed that leaves on the plants receiving the higher rates of N appeared to be larger than those on nil N plants, but the number of basal rosettes per square meter and rosettes per plant declined by 95 and 99% respectively as N rate was increased from 40 to 480 kg N ha^{-1}. Moreover, excess N fertilizer is detrimental to the environment. The most effective use of N fertilizer is usually a low rate (20–50 kg N ha^{-1}) in early spring to assist the plants' recovery from winter.

Martensson *et al.* (1998) studied the possibilities of improving N transfer from N_2-fixing plants to chicory by mycorrhiza. Chicory cultivars were intercropped with either peas (*Pisum sativum* L.) or red clover and inoculated with mycorrhiza isolates. At six months, the percentage of N in the chicory roots derived from transfer of legume N ranged from 20 to 34% and varied with fungal isolate. It was concluded that N transfer in intercropped chicory systems can be improved through the careful selection of suitable plant and mycorrhizal partners. Nevertheless, addition of selections of mycorrhiza to agricultural soils is inconsistent (Abbott and Robson, 1982).

V. GRAZING MANAGEMENT

A. Leaf and Stem Balance

The key objective in chicory grazing management is to maximize leaf production and minimize stem production (Hume *et al.*, 1995; Li *et al.*, 1997a; Moloney and Milne, 1993). Matthews *et al.* (1990) reported that Puna chicory developed more than 80% of stem in the total yield when not grazed in October or laxly grazed until early December. For chicory crops used for seed production, most of the yield consists of reproductive stems although high herbage mass (up to 25 t DM ha^{-1}) may be accumulated (Hare *et al.*, 1987). Stem is usually of low quality and animals avoid grazing mature stems. McCoy *et al.* (1997) observed that both calves and bulls selected leaves strongly over stem, and that mature beef cows clearly avoided grazing chicory stems. Therefore, the reproductive stems should be properly controlled if high quality feed is required.

Puna chicory cannot be used as a crop that accumulates large quantities of herbage to overcome feed shortages due to its stem production (Matthews *et al.*, 1990). Successful chicory production for grazing livestock depends on

achieving a balance between vigorous vegetative growth and herbage quality (Li *et al.*, 1994). Clark *et al.* (1990a) reported that chicory flowers and live leaves had higher dry matter digestibility values (81.0% and 77.0%, respectively) than the main stem (46.2%). Leaf yield rather than total yield should be optimized at each cutting or grazing due to the low digestibility of stem. Therefore, it may be preferable to sacrifice some DM production and keep the sward in a vegetative state by more frequent and intense grazing. It was suggested that 70:30% is the optimum leaf:stem ratio for high quality feed production (Clark *et al.*, 1990b).

B. Preference

Puna chicory is highly preferred by many farm animal species, such as deer, cattle, and sheep. In a series of grazing preference trials undertaken in New Zealand, red deer preferred red clover and chicory to most other pasture plant species (Hunt and Hay, 1990). In contrast, Belesky *et al.* (1996) observed growing lambs grazing chicory-cocksfoot pasture refused to eat chicory even though the sward was maintained in a vegetative state. These lambs, compared with ones grazing cocksfoot-white clover swards, had a lower average daily gain for the season (Belesky *et al.*, 1996). The high concentrations of secondary metabolites, including sesquiterpene lactones, tannins, and other phenolic compounds in some chicory cultivars (Barry, 1998), may affect grazer preference (Foster *et al.*, 2002).

C. Grazing Intensity and Frequency

Puna chicory produces excellent forage in terms of herbage yield and feed quality provided it is well managed. A number of experiments on the grazing management of Puna chicory have aimed to maximize leaf growth and minimize stem development (Clark *et al.*, 1990b; Hume *et al.*, 1995; Moloney and Milne, 1993). Grazing frequency has significant effects on the accumulated leaf and stem mass (Clark *et al.*, 1990b). Clark *et al.* (1990b) suggested that grazing every 4–5 weeks would provide near maximum leaf yield without large amounts of stem. Li *et al.* (1997b) found that a four-week grazing frequency accumulated the highest leaf and stem dry matter, and a one-week frequency the least. Belesky *et al.* (1999) also suggested that cutting frequency influenced DM yield, with canopies cut at six-weekly intervals producing 26% more herbage than canopies cut three-weekly. Similarly, Clark *et al.* (1990b) found that two four-weekly cuts had no effect on persistence or regrowth, whereas four two-week cuttings to ground level decreased plant density and regrowth. A grazing frequency of no greater than five weeks was

recommended by Matthews *et al.* (1990) to prevent reproductive stem becoming mature. Eight week cutting intervals produced a large amount of stem although DM yield was maximized (Clark *et al.*, 1990b). Jung *et al.* (1996) suggested that prolonged frequent harvesting may adversely affect forage mass and early spring growth in the subsequent year, whereas Volesky (1996) concluded that rotational grazing with a rest period of at least 24 days appeared to be the strategy that optimized leaf production while maintaining low numbers of bolting plants.

Grazing intensity had no effect on the total leaf production (Clark *et al.*, 1990b), but the proportion of stem increased as grazing intensity decreased (Li *et al.*, 1994). A 0–5 cm grazing residual produced the greatest leaf production, whereas a 15–20 cm residual had the greatest stem production for year 4 chicory pasture (Li *et al.*, 1994). However, there were no significant differences in either leaf or stem mass between grazing intensities (hard and hard-lax grazing) for year 1 chicory pasture (Li *et al.*, 1994).

Studies of root carbohydrate reserves in a glasshouse experiment (Li *et al.*, 1997c) showed that Puna chicory used its root carbohydrate reserves (fructose) for regrowth after defoliation, and thus required time to rejuvenate reserves. Therefore, it was concluded that Puna chicory was more sensitive to grazing frequency than grazing intensity. That is, Puna chicory can be grazed closely, but not frequently. Li *et al.* (1997c) confirmed, from three glasshouse experiments, that cutting frequency had a more negative impact than cutting intensity in relation to herbage production, root size, and root carbohydrate reserves, but that cutting intensity affected biomass allocation and regrowth of Puna chicory.

Appropriate grazing management controls the growth of primary reproductive stems of chicory in spring, but does not prevent the development of axillary, or secondary stems in summer and autumn (Li *et al*., 1997a,b,c), indicating buds produced in the previous year are vernalized in winter. Thin axillary stems develop regardless of whether or not plants are defoliated (Li *et al*., 1998; Moloney and Milne, 1993). However, these fine stems are not seen as limiting either quality or grazing control (Moloney and Milne, 1993). Overall, it is concluded that defoliation at 5–10 cm in height at three-week intervals in spring, and at 10–15 cm at five week intervals in summer and autumn, maximizes leaf formation and minimizes stem development of chicory (Li, 1997). Extending rest periods to allow development of 50-cm canopies favors stem production at the expense of leaf production. In this situation, chicory leaves can be grazed by high-producing animals and stems fed to non-lactating breeding animals as a maintenance diet. Immature stems of Puna chicory were readily grazed by dry cows in Pennsylvania (Jung *et al.*, 1996). However, if optimal grazing control is missed in spring, mechanical topping appears to be the only way to remove old stem stubble and control secondary stem development in summer.

VI. PERSISTENCE

A. Plant Density and Seedling Recruitment

Puna chicory loses about 30% of its population each year (Table IV). Seedling recruitment is unlikely in a mature chicory stand (Li *et al.*, 1997a) as it is for alfalfa (Lodge, 1991). Volesky (1996) observed that new seedlings were observed in autumn and spring but most of them did not survive, probably due to trampling associated with grazing or the extension of canopy cover from mature plants. Thus, persistence of chicory in a stand largely depends on the survival of the original plants. It is essential to maintain sufficient plant numbers in the sward to ensure a high yield (Li, 1997). Volesky (1996) suggested that a density of 43–48 plants m^{-2} appeared to be the maximum for established chicory swards from the second growing season, whereas Moloney and Milne (1993) recommended that a target plant density for mature stands was 18–24 plants/m^{-2}. Li *et al.* (1997a) concluded that the optimum plant density and plant size to maintain high herbage production were over 50 plants/m^{-2} with 2–4 shoots/$plant^{-1}$ in the soil and environmental conditions in New Zealand (Table IV).

Li *et al.* (1997a) found a strong linear relationship between plant density and shoots per plant with the plant size increasing from three shoots $plant^{-1}$ in year 2 up to seven shoots/$plant^{-1}$ in year 4 (Fig. 1). In the fourth year, although shoot density (shoots/m^{-2}) was similar to the density in previous years, shoot size (g DM/$shoot^{-1}$) was much smaller, resulting in significantly less herbage accumulation compared with younger chicory stands (Li *et al.*, 1997a). Under grazing conditions in New Zealand, once chicory density declined to 25 plants/m^{-2}, six or more shoots/$plant^{-1}$, or less than 150 shoots/m^{-2}, herbage production is likely to be 50% or less of its maxamium (Fig. 1). Li (1997) suggested that a chicory stand in this state needed to be re-sown or cultivated.

Table IV
Plant Density and Plant Size for Puna Chicory

Authors	Year 1	Year 2	Year 3	Year 4
	Plant density (number/m^{-2})			
Hume *et al.* (1995)	46	30	21	15
Volesky (1996)	48	46	n/a	n/a
Li *et al.* (1994; 1997a)	66	68	49	24
	Plant size (shoots/$plant^{-1}$)			
Li *et al.* (1994; 1997a)	2.9	2.7	4.1	6.7

n/a: not applicable.

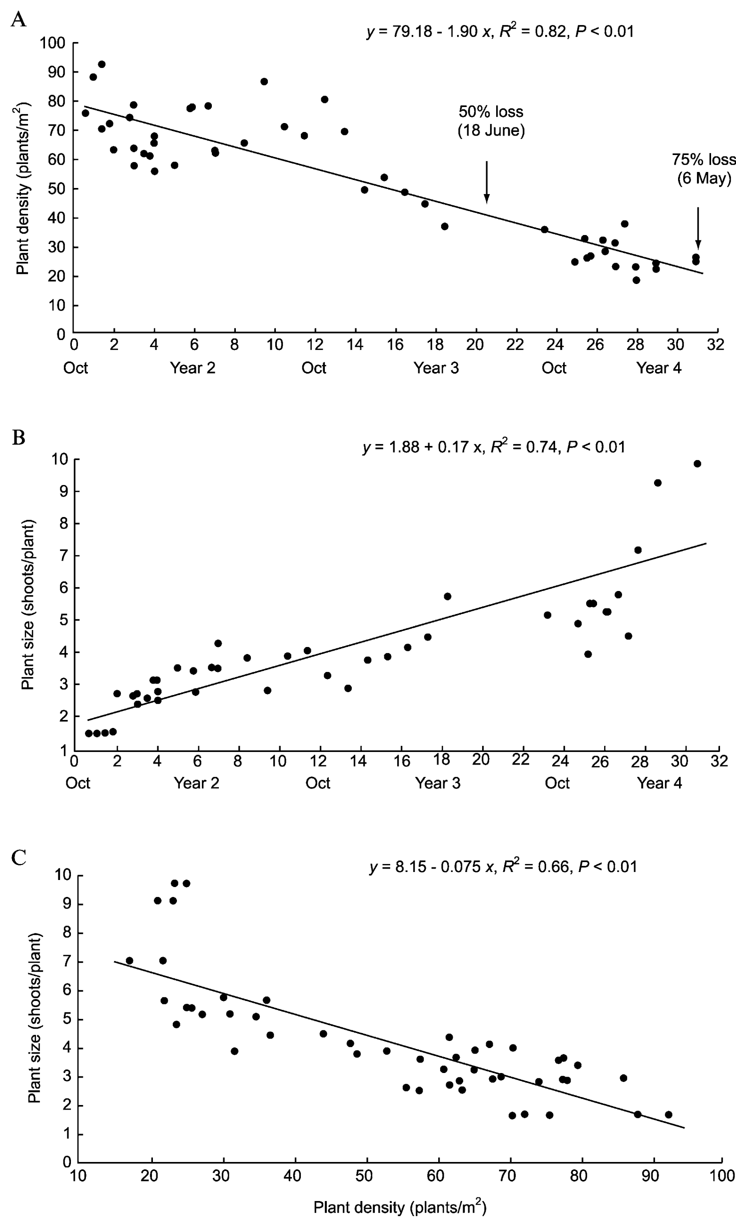


Figure 1 Plant density and plant size dynamics for Puna chicory over 3 years. (A) plant density versus plant age (month unit); arrows show predicted month for 50 and 75% plant losses; (B) plant size versus plant age (month unit); and plant size versus plant density (adapted from Li *et al.*, 1997a).

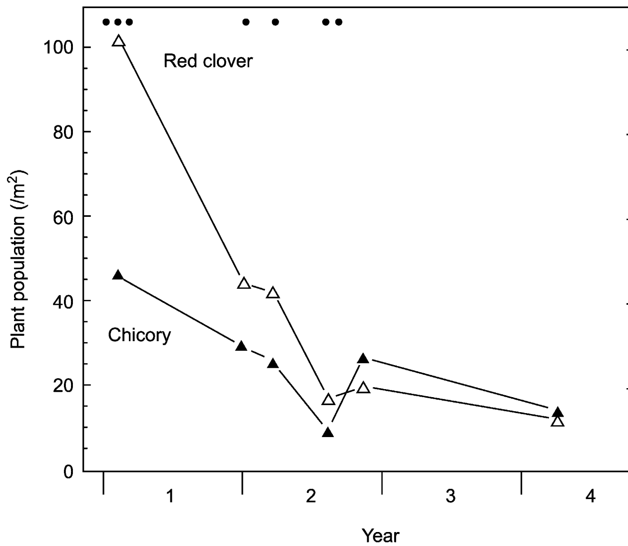


Figure 2 Mean plant population densities of Puna chicory (mean of all chicory pasture mixtures) and red clover during experiment. Dates when significant differences occurred between species are indicated ($* P < 0.05$; $** P < 0.01$; $*** P < 0.001$). Adapted from Hume *et al.* (1995).

In mixed pasture, although Puna chicory dominated the swards during the first three years, its yields were declining by year 4 (Hume *et al.*, 1995). Plant numbers, however, declined from 46 plants m^{-2} in the establishment year to 15 plants m^{-2} by year 4 (Fig. 2). Fraser *et al.* (1988) also observed that plant density of chicory declined over time in pastures, although relative yields remained similar over three years. This decline in plant density is common in chicory (Fraser *et al.*, 1988; Lancashire and Brock, 1983). However, the increased plant size due to splitting of the crown and development of more shoots per plant compensates for the continual decline in plant numbers, resulting in relatively constant yields at least over the first few years (Hume *et al.*, 1995; Li *et al.*, 1997a).

B. Factors Affecting Persistence

There are many factors that affect the persistence of chicory, such as grazing management, animal diet selection, fertilizer application, and diseases as well as soil and climatic conditions (Fig. 3). The decline with time in plant density in chicory appears to be inevitable under grazing (Table IV). However, chicory persists better under rotational grazing than set stocking

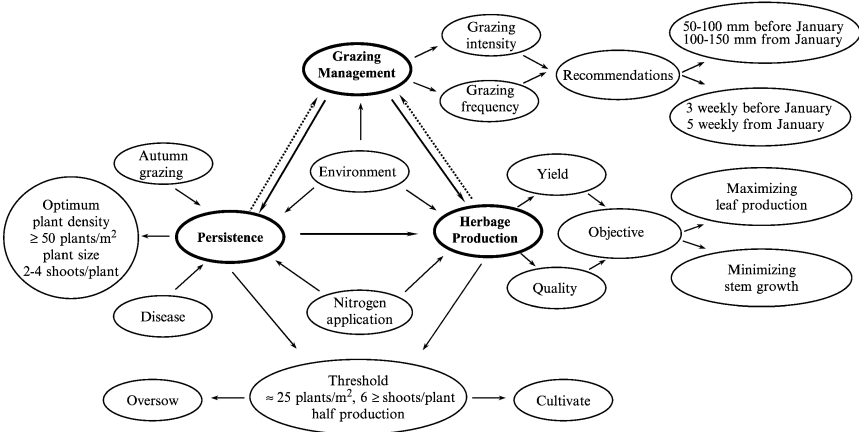


Figure 3 Flow chart for chicory management (adapted from Li, 1997).

(Lancashire and Brock, 1983). Li (1997) observed that all tagged chicory plants survived in plots that were not grazed for a growing season.

When grazed rotationally, chicory can be grazed to ground level at each grazing as it regenerates new shoots from the basal crown (Rumball, 1986). However, excessively frequent cutting or grazing is detrimental to the persistence of chicory (Fig. 1). Clapham *et al.* (2001) determined that 33% of the plants died during the first two growing seasons regardless of whether they were vegetative or reproductive the previous year. Surviving plants tended to alternate their growth form. Ninety-five percent of surviving 1997 vegetative plants switched to a reproductive form in 1998, and 67% of 1997 reproductive plants switched to a vegetative growth form in the subsequent year. These observations suggested that there are management and environment interactions that need to be clarified to understand the impact of management and grazing on chicory persistence.

Seasonality of grazing is also important for the persistence of Puna chicory. Li *et al.* (1994, 1997a) found that plant density decreased sharply during late spring and early summer where hard grazing was applied to control primary reproductive stem growth of young chicory stands (Li *et al.*, 1997a). However, grazing had less influence on persistence as plants aged. For instance, plant density remained constant during spring and summer for year 4 chicory pasture (Li *et al.*, 1994). It was observed that there was a vegetative shoot flush in autumn, which was important for the persistence and regrowth of chicory in the following season (Li *et al.*, 1997b). There was evidence to show that autumn grazing, especially hard grazing, was detrimental to plant persistence (Li *et al.*, 1997b). Therefore, spring and autumn grazing management is critical for the persistence of chicory. Less

grazing pressure through the growing season cannot be used to improve persistence without compromising leaf growth rate, but avoidance of grazing in late autumn will improve the persistence of chicory.

Nitrogen fertilizer can increase herbage production as discussed in the previous section. However, high N rates (200 kg ha^{-1}) were associated with declining plant density and regrowth (Clark *et al.*, 1990a). However, clipping cocksfoot-chicory mixtures at three- and six-week intervals that received only 35 kg N ha^{-1} (Belesky *et al.*, 1999), or rotational grazing of chicory-cocksfoot paddocks (Turner *et al.*, 1999), did not lead to the same loss of chicory from swards as Belesky *et al.* (2000) found on their N rate experiments in West Virginia.

Selective grazing can decrease the persistence of chicory. It was observed that sheep graze some plants, particularly the young and small plants, to ground level and remove all shoots above the crown, leaving other plants to produce reproductive stems (Li, 1997). Sheep re-grazed the new growth from previously grazed plants down to ground level again during the next grazing. This repeated hard grazing of some plants depleted the root carbohydrate reserves, reduced plant vigor, and finally killed the plants, as evidenced by the extreme defoliation treatment (removing all visible buds over 5 mm in length on the crown) in a glasshouse experiment (Li *et al.*, 1997c). Although nearly all plants that died succumbed to diseases eventually, the initial reason for their sensitivity to diseases was poor vigor due to excessive grazing (Li, 1997).

Sclerotinia spp. was reported to be the cause of plant death in some research (Arias-Carbajal, 1994; Hume *et al.*, 1995). Kemp *et al.* (2002) found that no disease was evident on chicory until the fourth year when *Sclerotinia* infections were found on a few plants in one experiment. Other pathogens (*Fusarium* spp. and *Pseudomonas* spp.) were also found on plants grown in field (Li *et al.*, 1997a) and in glasshouse experiments (Li *et al.*, 1997b), but with very low infection rate. Although a diminishing soil N supply and pathogens such as *Sclerotinia* spp. probably contributed to the poor persistence of chicory in some cases (Arias-Carbajal, 1994; Hare *et al.*, 1987; Moloney and Milne, 1993), improper management such as prolonged and heavy set stocking or grazing at high stocking rates during periods of heavy rain were likely to be the major cause of reduced persistence. Rumball *et al.* (2003a,b) selected for tolerance to *Sclerotinia* when breeding recent cultivars of chicory.

Summarizing the above evidence, chicory is a short term perennial species that can be productive for at least four years under grazing conditions. Proper management prolongs the lifespan of chicory. However, chicory should be kept well grazed to prevent the formation of flowering stems if high quality feed is required. Chicory should be grazed to below 10 cm at three weekly intervals in spring and early summer, and grazed to below 15 cm at five weekly intervals after mid-summer. Mechanical topping is an

option if optimal grazing control is missed in spring. The characteristics of a grazed chicory crop that has deteriorated to the point of not being able to accumulate half of its maximum herbage mass are 25 plants/m^{-2}, six or more shoots $plant^{-1}$, or less than 150 shoots/m^{-2}. Stands in this state need to be over-sown or re-sown (Fig. 3).

VII. NUTRITIVE VALUE

A. Mineral Contents

Chicory is rich in minerals. The ash content of chicory (188 g kg^{-1} DM) is substantially higher than that found in most perennial forages (90–110 g kg^{-1} DM) (Hoskin *et al.*, 1995). Scales *et al.* (1994) reported that the mineral contents of chicory were similar to alfalfa and generally higher than those of grasses. In general, most of the macro-minerals in chicory were similar to or exceeded those found in grasses and legumes except for total N (Table V) (Barry, 1998; Belesky *et al.*, 2001; Crush and Evans, 1990; Jung *et al.*, 1996). Barry (1998) found that chicory contained very low concentrations of silicon, which made it more readily digested than plants in which silicon was deposited, as silicon can alter the mechanical properties of herbage (Crush and Evans, 1990). Puna chicory has been reported high in the micro-minerals S, B, Mn, molybdenum and Zn (Rumball, 1986). Active accumulation of minerals indicates the need for high nutrient input (such as boron) to sustain production, especially on soils with marginal fertility (Belesky *et al.*, 2001).

There is some evidence that the presence of forb species in swards can result in greater contents of minerals in herbage compared with grass-only swards (Belesky *et al.*, 2001; Fisher *et al.*, 1996). Mineral concentrations in Puna chicory met or exceeded recommended dietary mineral requirements of

Table V
Macro Mineral Contents (g kg^{-1} DM) in Puna Chicory, Alfalfa, and Phalaris at Vegetative Stage

Mineral contents	Chicory[a]	Alfalfa[b]	Phalaris[b]
Calcium	14.9	10–27	2.0–4.5
Phosphorus	3.4	2.7–4.8	2.6–4.3
Sodium	2.1	1.2	
Potassium	36.4	22–32	23–46
Magnesium	2.8	2.8–7.0	2.1–3.5
Total nitrogen	19.7	39–51	28–43

Adapted from [a]Barry (1998); [b]Pinkerton *et al.* (1997), averaged for all available data at adequate concentration.

lactating dairy cows and beef cattle (Belesky *et al.*, 2001; Jung *et al.*, 1996). However, swards with low amounts of chicory were likely to be marginal in terms of meeting mineral nutrient requirements of livestock (Belesky *et al.*, 2001). Jung *et al.* (1996) suggested that the high magnesium concentration in chicory in early spring may reduce the risk of grass tetany. Zinc levels in chicory ranged from 31 to 385 mg kg^{-1} in the field and 12 to 102 mg kg^{-1} in the glasshouse (Crush and Evans, 1990), exceeding normal values in perennial ryegrass/white clover pasture. Zinc has been found to be effective against facial eczema in lambs (Aman, 1985). However, a recent study on Cu concentration in lamb liver showed that lambs grazing chicory had higher liver Cu concentrations (3608 μmol kg^{-1}) than those grazing pasture (2453 μmol kg^{-1}), due to higher Cu concentration in chicory. This may impair market access for sheep products overseas (Clark, 1995).

B. Organic Components

Puna chicory has variable crude protein levels of 134–244 g kg^{-1} (Crush and Evans, 1990). Crude protein in chicory is lower than legumes, but higher than perennial ryegrass (Table VI). Pure chicory swards grown in central Pennsylvania averaged 230 g kg^{-1} crude protein under intensive defoliation and 140 g kg^{-1} protein when managed in an infrequent defoliation regime (Jung *et al.*, 1996). An average crude protein of 183 g kg^{-1} was obtained from pre-grazed chicory in Oklahoma (Volesky, 1996). Low N contents in chicory have also been observed when it was grazed by calves (Clark *et al.*, 1990a; Fraser *et al.*, 1988), or fed indoors to sheep (Komolong *et al.*, 1992)

Table VI
Organic Components (g kg^{-1} DM) in Puna Chicory, White Clover, Lotus, and Perennial Ryegrass at the Vegetative Stage and Secondary Phenolic Compounds in Chicory (g kg^{-1} DM)

	Chicory	White clover	Lotus	Perennial ryegrass
Crude protein[a]	243	280	257	201
Hemicellulose[a]	23	52	70	245
Cellululose[a]	113	153	121	183
Lignin[a]	33	27	35	18
Soluble sugar[b]	111			74
Pectin[b]	98			10
Metabolizable energy (MJ kg^{-1} OM)[b]	13.7			12.3
Extractable condensed tannin[b]	1.7		36.1[c]	0.9
Sesquiterpene lactones[b]	3.6			
Cichoriin[b]	0.5			
Chicoric acid[b]	5.8			

References: [a]Fraser and Rowarth (1996); [b]Barry (1998); [c]Min *et al.* (1997).

and to deer (Hoskin *et al.*, 1995; Niezen *et al.*, 1993a). Both N intake and rumen ammonia concentration were lower for lambs grazing chicory, as a consequence of the generally lower N concentration in chicory (Barry, 1998). Crude protein concentration seemed likely to be a more limiting factor in production of some types of beef cattle on chicory than its energy values, and supplementation of protein may be required for optimum utilization under some conditions (Collins and McCoy, 1997). However, despite the lower N intake, rumen N loss was less with chicory. Komolong *et al.* (1992) found duodenal flow of non-ammonia N was similar for lambs grazing cocksfoot and chicory, with loss of N across the rumen being lower for lambs grazing chicory (23%) than lambs grazing cocksfoot (39%).

Puna chicory contains higher concentrations of soluble sugar and pectin (readily fermentable carbohydrates, RFC) and lower concentrations of cellulose and hemicellulose (structural carbohydrates, SC) than perennial ryegrass (Table VI). The metabolizable energy (ME) concentration of chicory is also higher than that of perennial ryegrass (Table VI). Collins and McCoy (1997) pointed out that low concentration of fiber in chicory leaf might limit utilization of pure chicory. Volesky (1996) suggested that chicory grown in combination with other forages might overcome the low dry matter content encountered in pure chicory stands.

C. Organic Matter Digestibility

Puna chicory has high feeding value for ruminants. The OM digestibility of chicory is higher than grass-based pastures (Holden *et al.*, 2000; Kusmartono *et al.*, 1997) and similar to alfalfa (Turner *et al.*, 1999). Min *et al.* (1997) found that feeding value of chicory for deer was equivalent to red clover and higher than perennial ryegrass/white clover pastures. Kusmartono (1996b) also found that chicory had a higher relative metabolic energy value than perennial ryegrass-white clover pasture, and even red clover and white clover during summer and autumn. Chicory has high digestibility and a low fiber concentration, which are desirable for growing and lactating ruminants (Turner *et al.*, 1999). Based on the high OM digestibility, Collins and McCoy (1997) reported that the energy value of chicory for ruminants was sufficient to meet the needs of beef brood cows throughout the year and those of growing cattle at moderate levels of gain.

The higher DM and OM digestibility values of Puna chicory are due to a higher RFC:SC ratio (1.15) of chicory compared with perennial ryegrass-white clover pasture (1.00) (Hoskin *et al.*, 1995; Kusmartono *et al.*, 1996a). Similarly, Ulyatt and MacRae (1974) concluded that the higher apparent digestibility value of white clover relative to perennial ryegrass was due to its higher RFC:SC ratio (1.17 versus 1.00). However, apparent digestibility values of fiber for chicory were found to be lower than for perennial

ryegrass/white clover pasture (Hoskin *et al.*, 1995). Kusmartono *et al.* (1996b) suggested the low neutral detergent fiber (NDF) digestibility was probably due to low rumen pH.

The NDF and ADF of chicory are even lower than for alfalfa (Turner *et al.*, 1999). This suggests that chicory would provide more energy per kg of DM eaten than alfalfa. Although fiber concentrations in chicory are low compared with those of common cool-season grasses and legumes (Collins and McCoy, 1997), ample mineral concentrations in chicory could lead to overall improvements in ruminant utilization of forage mixtures that include chicory (Belesky *et al.*, 2001). However, the low NDF and ADF values for chicory could lead to problems with rumen health (Holden *et al.*, 2000). Dietary fiber levels could be increased by inclusion of a cool-season grass in mixtures with chicory (Collins and McCoy, 1997). Belesky *et al.* (1999) suggested that growing chicory in combination with other plant species may affect the nutritive value of the diet on offer and could lead to improved forage utilization efficiency, depending on the dietary component selection by the grazer. Holden *et al.* (2000) stated that the high feed quality of chicory should support high levels of liveweight gain or milk production, but may be best used in combination with other forages to reduce the negative effect of lower fiber level.

Nitrogen fertilizer also affects the nutritive value of Puna chicory. As the level of N fertilizer increases, herbage N increases and NDF and ADF decreases, suggesting an improvement in nutritive value; however, *in vitro* organic matter digestibility (IVOMD) tended to decrease as the level of N fertilizer increased (Turner *et al.*, 1999). On the other hand, fertilizing chicory with excess N (400 kg ha^{-1}) could lead to nitrate-N accumulation in chicory herbage with the potential to cause nitrate poisoning in livestock (Belesky *et al.*, 2000).

Turner *et al.* (1999) measured IVOMD using cocksfoot mixtures with different proportions of chicory and alfalfa and found that the pure chicory and pure alfalfa had lower IVOMD than did pure cocksfoot (Fig. 4). In cocksfoot mixtures with 20, 40, and 60% chicory or 40 or 60% alfalfa, IVOMD was greater compared with 100% cocksfoot, chicory, or alfalfa. These results suggested that a mixture of chicory or alfalfa with cocksfoot allowed efficient breakdown and usage of OM and NDF in the rumen, thus increasing OM digestibility and improving nutritive value relative to either forage alone.

D. Secondary Phenolic Compounds

Chicory contains a low concentration of condensed tannins (1.7 g kg^{-1}) that is unlikely to slow the *in vitro* rumen degradation of leaf protein (Barry, 1998). Jackson *et al.* (1996) suggested that the minimum concentration of condensed tannins in grazed forages to prevent bloat in cattle and to increase

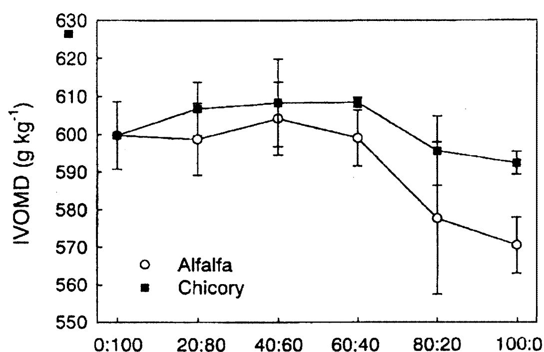


Figure 4 *In vitro* organic matter disappearance using different proportions of cocksfoot plus chicory fertilized with NH_4NO_3 at 100 kg ha^{-1} or plus alfalfa. Error bars indicated SE of the mean (adapted from Turner *et al.*, 1999).

wool growth was approximately 5 g kg^{-1} DM. Deaker *et al.* (1994) reported that chicory did not contain useful amounts of condensed tannins (1.36 g kg^{-1} DM), as measured by the butanol/HCl method of Terrill *et al.* (1992), to protect protein from rumen degradation. Similarly, Kusmartono (1996b) found that the action of condensed tannins reduced rumen ammonia concentration in deer fed chicory, but did not affect protein solubility. Nevertheless, the low concentration of condensed tannins in chicory may be partly responsible for the higher growth rates of ruminants fed chicory compared with those fed perennial ryegrass/white clover pasture (Hoskin *et al.*, 1995; Kusmartono *et al.*, 1996a).

Chicory also contains low concentrations of sesquiterpene lactones (lactucin, lactupicrin, and 8-deoxylactucin), chicoriin (a coumarin) and chicoric acid (a caffeic acid derivative) (Barry, 1998). These are part of the defensive chemistry of the chicory plant, with sesquiterpene lactones and chicoriin deterring consumption by insects. Sesquiterpene lactones and chicoric acid are also present in root tissue at similar concentrations, and may also function by countering potential infection of the plant by soil-borne microorganisms (Barry, 1998).

VIII. ANIMAL PERFORMANCE

A. Voluntary Feed Intake

Deer have a higher voluntary feed intake (VFI) when grazed on chicory rather than on perennial ryegrass-white clover pasture (Min *et al.*, 1997). Kusmartono (1996) found that VFI of deer grazing chicory was higher than

that of deer grazing perennial ryegrass-based pasture by 56% during summer, 26% during autumn, and 15% during spring. Further research showed that the fractional degradation of large particles to small particles and the fractional disappearance of DM from the rumen were both approximately twice as fast for deer fed chicory as for those fed perennial ryegrass (Kusmartono *et al.*, 1996a,b). The faster clearance of DM from the rumen provides an opportunity for increased VFI, as this has long been recognized as a major process determining intake and nutritive value of forage (Black *et al.*, 1982). Some deer (60%) could break down swallowed chicory to below the critical particle size (Domingue *et al.*, 1991) without ruminating at all (Kusmartono *et al.*, 1996b). This suggested that after chicory had been chewed and swallowed it then disintegrated extremely rapidly in the rumen, probably due to its high ratio of RFC:SC and low content of silicon (Barry, 1998).

Tinworth *et al.* (1999) noted that chicory has a low DM content (113 g kg^{-1} fresh weight) that might limit voluntary feed intake, as a comparison with literature values showed that DM contents of fresh forages with less than 150 g DM kg^{-1} fresh weight are likely to restrict the voluntary DM intake of ruminants. Collins and McCoy (1997) also suggested that a high moisture concentration and low fiber concentration might affect chicory utilization under some conditions. Tinworth *et al.* (1999) showed that wilting chicory increased its voluntary feed intake by red deer in New Zealand.

B. Liveweight Gain

Sheep, deer, and cattle grazed on Puna chicory have all exhibited greater liveweight gains in comparison to perennial ryegrass/white clover pasture (Table VII). The liveweight gain was approximately 240 g/day^{-1}, up to 290/g day^{-1}/$head^{-1}$, for lambs grazed on chicory, which was similar to lambs grazed on legumes such as alfalfa and white clover, and higher than lambs grazed on grasses (Table VII), especially in late spring and summer when conventional pastures often have lower feed quality. Holst *et al.* (1998) concluded that both chicory and alfalfa pastures produced sufficient DM of quality forage to finish lambs over summer. In three of five lamb groups, growth rate on chicory pastures was significantly greater than on alfalfa. Calves grazed on chicory gained 900 g day^{-1} when offered chicory *ad lib.* (Fraser *et al.*, 1988).

Kusmartono *et al.* (1996b) compared relative feeding values of chicory, red clover and perennial ryegrass/white clover pastures for grazing red deer and found that the feeding value of chicory and red clover were superior to that of perennial ryegrass/white clover pasture in autumn, spring, and summer. The feeding value of chicory for deer was higher than that of red clover in autumn (157 versus 126), similar in spring (115 versus 114), but

Table VII
Liveweight Gain (g day^{-1}) of Lamb, Bulls, and Deer Grazing Different Pastures

Season and country	Chicory	Alfalfa	Cocksfoot	Perennial ryegrass	White clover	References
			Lamb			
Spring, Australia	264	230				Holst *et al.* (1998)
Spring, New Zealand	290			227	320	Cruickshank (1986)
Late spring, New Zealand	273		205			Komolong *et al.* (1992)
Summer, New Zealand	146	146	115	104		Young *et al.* (1994)
Late spring/early summer, Australia	243	233				Hopkins *et al.* (1995)
Summer/early autumn, New Zealand	281	236	145–172 (grass average)			Scales *et al.* (1994)[a]
Summer/early autumn, New Zealand	192			121	226	Fraser and Rowarth (1996)[b]
			Friesan bull calves			
Late summer/autumn, New Zealand	905			700[d]		Fraser *et al.* (1988)
			Deer[c]			
Autumn, New Zealand	282			191[d]		Kusmartono *et al.* (1996a)
	154			224[d]		Hoskin *et al.* (1999)
Winter, New Zealand	160			159[d]		Kusmartono *et al.* (1996a)
	166			172[d]		Hoskin *et al.* (1999)
Spring, New Zealand	283			266[d]		Kusmartono *et al.* (1996a)
	344			289[d]		Hoskin *et al.* (1999)

[a]Averaged over two experiments; grass average, liveweight gain range for grass pastures (cocksfoot, perennial ryegrass or tall fescue).
[b]Averaged liveweight gain over 3 years.
[c]Liveweight for stags, averaged over red deer and hybrid deer (0.25 elk; 0.75 red deer).
[d]Perennial ryegrass/white clover pastures.

lower in summer (114 versus 124), when all data for deer were expressed relative to liveweight gain on perennial ryegrass/white clover pasture being 100 (Kusmartono *et al.*, 1996b).

Komolong *et al.* (1992) detailed the digestive processes of lambs grazed on Puna chicory and Wana cocksfoot in New Zealand. Lamb growth rate over six weeks was faster on chicory (268 g day^{-1}) than Wana cocksfoot (205 g day^{-1}). Although digestible OM intake (DOMI) and N intake were lower on Puna chicory (16.10 and 0.71 g kg^{-1} liveweight day^{-1}) than Wana cocksfoot (26.69 and 1.39 g kg^{-1} liveweight day^{-1}), non-ammonia N (NAN) flow at the duodenum was similar (0.70 vs. 0.85 g kg^{-1} liveweight day^{-1}) mainly due to variable N loss as ammonia across the rumen wall. None of the N consumed by lambs grazing chicory was lost as ammonia, while 39% of the N consumed by those grazing Wana cocksfoot was lost as ammonia from the rumen. Komolong *et al.* (1992) argued that the disparity in liveweight gain of lambs grazing chicory and cocksfoot was related to differences in the balance of nutrients rather than the intake quantity or supply of any one nutrient. This was shown in the ratio of duodenal NAN:DOMI for chicory being 43.5 which was similar to legumes, but the ratio for cocksfoot (31.9) was lower than for other grasses. They concluded that the nutritive value of chicory and cocksfoot for lamb growth can be best described by NAN:DOMI ratio (Table VIII).

C. Carcass Weight, Meat Quality, and Wool Growth

Hopkins *et al.* (1995) found that lambs grazing chicory or alfalfa exhibited similar carcass compositions in terms of fatness, weight, pH (<5.6), meat color value, tenderness, and flavor. There was no difference in leanness of the lambs grazing chicory or alfalfa (Hopkins *et al.*, 1995). Young *et al.* (1994) also found no difference between samples from lambs fed chicory or alfalfa in terms of flavor and overall acceptability. Hopkins *et al.* (1995)

Table VIII
Sites of Organic Matter (OM) and Nitrogen (N) Digestion in Lambs Grazing Puna Chicory or Wana Cocksfoot (Adapted from Komolong *et al.*, 1992)

	Chicory	Cocksfoot
Liveweight gain (g day^{-1})	268	205
In vitro OM digestibility (g kg^{-1})	726	742
Digestible OM intake (g kg^{-1} liveweight day^{-1})	16.1	26.7
Nitrogen intake (g kg^{-1} liveweight day^{-1})	0.71	1.39
Duodenal non-ammonia N flow (g kg^{-1} liveweight day^{-1})	0.70	0.85
Rumen ammonia (mg N l^{-1})	156	313

concluded that finishing lambs on chicory produced meat that is as acceptable as that from lambs fed alfalfa, based on both objective and subjective criteria. Scales (1993) reported that there was no effect of forage type on leanness of lambs grown at 200 g day^{-1}, nor was there any effect of forage type and liveweight on meat quality when Dorset, Suffolk cross, or Coopworth lambs weighing about 30 kg in January were offered a range of forages including high-endophyte Nui ryegrass-dominant pasture, white clover-dominant pasture, Moata or Concord ryegrass, alfalfa, rape (*Brassica* spp.), or chicory.

Deer grazing on chicory had significantly higher carcass weight compared with deer grazing on perennial ryegrass-white clover pasture due to greater liveweight gain and higher dressing out percentage at slaughter (Kusmartono *et al.*, 1996a; Min *et al.*, 1997). Kusmartono *et al.* (1996a) reported that red deer and hybrid stags grazing chicory had higher carcass weight by one year of age (63.2 and 73.0 kg) than those grazing perennial ryegrass-white clover pasture (56.6 and 57.0 kg), and the dressing out percentage of deer fed chicory was significantly higher than for those fed perennial ryegrass/white clover pasture.

Sheep grazed on Puna chicory had higher greasy wool production than sheep grazed on perennial ryegrass and plantain (*Plantago lanceolata* L.), but had lower greasy wool production than sheep grazed on white clover and birdsfoot trefoil over three years (Table IX).

D. Deer Velvet Production

Grazing one-year-old red deer on Puna chicory advanced the mean date of the first cut of velvet antler by 28 days, and increased total velvet antler weight by increasing the length of time for total velvet growth compared to deer grazing perennial ryegrass-white clover pasture (Kusmartono *et al.*, 1996a; Min *et al.*, 1997). Min *et al.* (1997) found that initiation of velvet growth was correlated with liveweight, with each 10 kg increase in liveweight advancing

Table IX
Effect of Pasture Species on Greasy Wool Production Over 83 Days (Year 1) and 120 Days (Years 2 and 3) in Summer/Early Autumn (Adapted from Fraser and Rowarth, 1996)

Pastures	Chicory	White clover	Lotus	Plantain	Perennial ryegrass
Year 1	1.62	1.79	n/a	1.48	1.42
Year 2	2.15	2.48	2.26	1.61	1.69
Year 3	2.54	2.69	2.86	1.79	1.69

n/a, not available.

the dates of pedicle initiation, commencement of velvet growth, and first velvet cutting by 10, 18, and 13 days, respectively. These studies indicated chicory has a potential role in stimulating earlier development of the pedicle and faster velvet antler growth for one-year-old stags, which may enable one year old deer grazing on chicory to produce two cuts of velvet in one season (Min *et al.*, 1997). However, there appears to be no effect of chicory on the velvet antler growth of adult stags (Cosgrove *et al.*, 1995). Semiadi *et al.* (1993) found no difference in the velvet antler weight of young stags grazing either red clover or perennial ryegrass-white clover pasture, even though liveweight gain responses were higher for deer grazing red clover.

E. Milk Production

Dairy cows in Pennsylvania grazing on Puna chicory had increased milk production compared to those grazing a mixture of cool-season grasses and white clover (Jung *et al.*, 1994). Waugh *et al.* (1998) compared crops of Puna chicory and Barkant turnips fed as supplements to dairy cows grazing pasture at Hamilton, New Zealand. Cows had similar milk-solids (MS) responses on chicory and turnips (40–41 g MS kg^{-1} DM) when offered 4 kg DM/cow day^{-1} of crop and 25 kg DM/cow day^{-1} of pasture. However, the milk from dairy cows fed a sole chicory diet has been found to have a bitter taint, and for this reason chicory feeding to dairy cows has been limited to 2 hours per day, generally following the morning milking, to restrict chicory intake to about 25% of the total daily DM intake (Barry, 1998). Degradation products of the sesquiterpene lactones, namely dihydrolactucin, tetrahydrolactucin, and hydroxypenyacetic acid have been identified as the taint compounds in the milk of chicory-fed cows (Visser, 1992). Forage chicory cultivars bred with lower levels of the sesquiterpene lactones are most unlikely to cause a taint or bitter aftertaste in the milk (Rumball *et al.*, 2003b).

F. Animal Health

Puna chicory may offer the potential for reduced adverse effects of internal parasites, and thus reduced anthelmintic use. Conventionally, farmers rely upon the routine use of anthelmintics to control internal parasites, and their use has proved to be highly cost-effective (Marley *et al.*, 2003). However, several factors, including the emergence of parasite resistance to anthelmintics, are forcing farmers to seek alternative approaches to parasite control. Scales *et al.* (1994) found lambs grazing chicory in autumn were unaffected by gastrointestinal nematodes, while parasitized lambs grazing grass pastures exhibited lower carcass weights than anthelmintic treated lambs. Niezen *et al.* (1998) found that the number of larvae of gastrointestinal nematodes

recovered was consistently greater from ryegrass and Yorkshire fog (*Holcus lanatus* L.), lower from chicory, alfalfa, and white clover and intermediate from cocksfoot, tall fescue, and prairie grass. Under UK environmental conditions, lambs with naturally acquired Helminth infections that were grazing chicory and birdsfoot trefoil had fewer Helminth parasites than sheep that were grazing ryegrass/white clover (Marley *et al.*, 2003).

Scales *et al.* (1994) suggested the higher soluble carbohydrate and mineral content and presence of condensed tannins in chicory enabled lambs grazing chicory to cope better with parasitism than lambs grazing grass pastures. Niezen *et al.* (1993b) suggested that the low concentration of condensed tannins in chicory offered animals some protection from internal parasitism (Niezen *et al.*, 1993b). However, Hoskin *et al.* (1999) argued that it was unlikely that the trace amount of condensed tannins in chicory had any affect as there was no difference in the condensed tannins concentration of chicory and perennial ryegrass-white clover pastures. One of the reasons for reduced parasite problems with chicory is probably its taller growth habit relative to grasses with fewer infective larvae reaching the stratum that is consumed by grazing animals. This suggests that the use of different herbage species may play an important role in parasite control. Another possible reason is that some of the secondary phenolic compounds in chicory may inhibit the growth of infective larvae (Barry, 1998). These phenolic compounds could potentially affect other organisms including perhaps gastrointestinal nematode and lungworm larvae (Hoskin *et al.*, 1999).

IX. CONCLUSIONS

Chicory produces a large quantity of high quality forage in the warm season. A forage production of 7–9 t ha^{-1} is very common for pure chicory stands for the first two or three years under grazing conditions. Chicory makes a substantial contribution to swards when mixed with grasses and legumes, especially in spring and summer, which can improve the feed quality on offer to livestock. The high feed quality and production of chicory in summer complements conventional pastures that often have poor feed quality and low production over summer due to approaching plant maturity and moisture stress.

Chicory has a high feeding value and high voluntary feed intake with great potential for finishing lambs, deer, and cattle. Lambs and deer grazed on chicory have a similar growth performance to those grazing forage legumes and better than those grazing grass-based pastures. Grazing chicory had no adverse effect on carcass compositions in terms of fatness, weight, pH, meat color value, tenderness, and flavor. However, the milk from dairy

cows fed with sole chicory diets was found to have a bitter taint due to its high levels of the sesquiterpene lactones in Puna chicory. The new forage chicory variety "Choice," with lower levels of the sesquiterpene lactones, would be most unlikely to cause a taint or bitter aftertaste in the milk.

Grazing on chicory does not cause bloat in cattle. Chicory has potential for reduced adverse effects of internal parasites, thus reducing anthelmintic use. The higher soluble carbohydrate and mineral content and presence of condensed tannins and phenolic compounds in chicory have most likely contributed to the superior ability to cope with parasitism for lambs grazing chicory than lambs grazing grass-based pastures.

Puna chicory responds to warm temperatures quickly. The fast growth rate of chicory in the late spring and early summer results from rapid development of reproductive stems. The key objective in chicory grazing management is to achieve high herbage production without prejudicing the feed quality. Puna chicory can tolerate hard grazing but not excessively frequent grazing. It is suggested that grazing below 10 cm in height at three-week intervals in spring, and below 15 cm at five week intervals in summer and autumn, maximizes the leaf formation and minimizes stem development of chicory. Extending rest periods to allow development of 50-cm canopies favored stem production at the expense of leaf production. However, if optimal grazing control is missed in spring, mowing appears to be the only way to remove old stem stubble and control secondary and axillary stem development in summer.

The decline in plant density in chicory appears to be inevitable under grazing. Frequent hard grazing, especially in late autumn, is particularly detrimental to the persistence of chicory. Avoidance of winter grazing and not grazing too frequently will prolong the lifespan of chicory. Given good management, chicory can be productive for at least four years under grazing conditions.

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Pre-Sowing Seed Treatment—A Shotgun Approach to Improve Germination, Plant Growth, and Crop Yield Under Saline and Non-Saline Conditions

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Rapid seed germination and stand establishment are critical factors to crop production under salt-stress conditions. In many crop species, seed germination and early seedling growth are the most sensitive stages to salinity stress. Salinity may delay the onset, reduce the rate, and increase the dispersion of germination events, leading to reductions in plant growth and final crop yield. The adverse effects of salt-stress can be alleviated by various measures, including seed priming (a.k.a. pre-sowing seed treatment). The general purpose of seed priming is to partially hydrate the seed to a point where germination processes are begun but not completed. Most priming treatments involve imbibing seed with restricted amounts of water to allow sufficient hydration and advancement of metabolic processes but preventing germination or loss of desiccation tolerance. Treated seeds are usually redried before use, but they would exhibit rapid germination when re-imbibed under normal or stress conditions. Various seed priming techniques have been developed, including hydropriming (soaking in water), halopriming (soaking in inorganic salt solutions), osmopriming (soaking in solutions of different organic osmotica), thermopriming (treatment of seed with low or high temperatures),

solid matrix priming (treatment of seed with solid matrices), and biopriming (hydration using biological compounds). Each treatment has advantages and disadvantages and may have varying effects depending upon plant species, stage of plant development, concentration/dose of priming agent, and incubation period. In this article, we review, evaluate, and compare effects of various methods of seed priming in improving germination of different plant species under saline and non-saline conditions. We also discuss the known metabolic and ultra-structural changes that occur during seed priming and subsequent germination. To maximize the utility of various seed priming techniques, factors affecting their efficiency must be examined and potential benefits and drawbacks determined. For example, quality of the seed before treatment, concentration/dose of priming agent, time period for priming, and storage quality of the seed following priming treatment must be carefully determined. Furthermore, such assessments must be based on large-scale experiments if seed priming is to be used for large-scale field planting. A better understanding of the metabolic events that take place in the seed during priming and subsequent germination will improve the effective application of this technology. The incorporation of advanced molecular biology techniques in seed research is vital to the understanding and integration of multiple metabolic processes that can lead to enhanced seed germination, and consequently to improved stand establishment and crop yield under saline and non-saline conditions.

I. INTRODUCTION

Seed germination is a complex and dynamic stage of plant ontogeny, with a number of interactive metabolic processes undergoing changes from a storage phase to a mobilization phase (Bewley and Black, 1994). The multitude of simultaneous metabolic processes taking place in germinating seed makes it difficult to examine events related to the initiation of the germination process. In an entire seed, the catabolic processes in the storage tissues can confound measurements and interpretation of anabolic and growth processes occurring in the developing embryo. This problem may be even more complex when there is non-genetic variation among seeds, which affects the time to complete the germination. The time from sowing to seedling establishment is of considerable importance in crop production and has major impacts on plant growth, final yield, and post-harvest seed quality (Wurr and Fellows, 1985). In general, seed germination entails three distinct phases: *phase I* is the imbibition process, in which water is taken up by the seed but little metabolic activity takes place; *phase II* is a lag phase in which there is little water uptake but considerable metabolic activity; and *phase III* is marked by an increase in water content coinciding with radicle growth and

emergence (Bradford, 1995). The length of phase III is important because germination is considered complete when embryo growth is initiated. During seed germination, the soil environment is often not conducive to rapid germination and seedling growth. For example, adverse abiotic and biotic stresses, such as low and high temperatures, soil crusting, shortage or excess of water, salinity, pathogenic diseases, and insects, can reduce the rate or completely inhibit seed germination and seedling emergence.

Although dry seed is often characterized as having a low rate of metabolism due to low water content (~5–10%), it does not lack the potentiality for active metabolism, and at least a few enzymes remain active (Ashraf *et al.*, 2003b; Filho and Sodek, 1988; Guerrier, 1988; Poljakoff-Mayber *et al.*, 1994). In fact, desiccated seed is a well-equipped functional unit that can undergo many biochemical reactions if the initial hydration of proteins, in particular enzyme proteins, has taken place (Bewley and Black, 1982; Mayer and Poljakoff-Mayber, 1989). Although only a few minor changes may be observed in chemical composition of dry seed, as soon as the seed is hydrated, marked chemical changes such as breakdown and transport of reserve materials, especially transport from endosperm or cotyledons to the growing parts of the embryo, and synthesis of new materials may occur (Mayer and Poljakoff-Mayber, 1989).

One of the first physiological disorders taking place during seed germination under salt stress is a decrease in water uptake by the seed due to low water potential of the germination medium. In addition to causing various structural changes at different levels of organization in the seed, slow rate of imbibition may lead to a series of metabolic changes, including up-regulation or down-regulation of enzyme activities (Ashraf *et al.*, 2002; Filho and Sodek, 1988; Guerrier, 1988), perturbance in the mobility of inorganic nutrients to developing tissues (Ashraf and Wahid, 2000; Petruzzelli *et al.*, 1991), disturbance in N metabolism (Dell'Aquila and Spada, 1993; Yapsanis *et al.*, 1994), imbalances in the levels of plant growth regulators (Khan and Rizvi, 1994), reduction in hydrolysis and utilization of food reserves (Ahmad and Bano, 1992; Mondal *et al.*, 1988), and accumulation of compatible osmotica such as soluble sugars, free proline, and soluble proteins (Ashraf *et al.*, 2003b; Poljakoff-Mayber *et al.*, 1994; Zidan and Elewa, 1995). These processes may lead to poor or complete lack of seed germination under saline conditions (Poljakoff-Mayber *et al.*, 1994). However, rapid and uniform seed germination and early seedling establishment are critical components for crop production under saline conditions. Seed germination and early seedling growth are generally the stages most sensitive to salt stress, as plant salt tolerance usually increases with plant ontogeny (Foolad, 2004). Thus, if the effect of salt can be mitigated at early stages, the chance of establishing a successful crop under salt stress will be improved (Ashraf *et al.*, 2003b; Foolad, 2000; Sallam, 1999).

Soil salinity is a major environmental constraint to crop productivity worldwide. It is estimated that approximately 20% of cultivated lands and 33% of irrigated agricultural lands in the world are afflicted by excessive salinity (Epstein *et al*., 1980; Flowers *et al*., 1986; Francois and Maas, 1994; Rowley, 1993; Szabolcs, 1992; Tanji, 1990). Furthermore, salinized areas are increasing at a rate of 10% annually (Kalaji and Pietkiewica, 1993; Syverstein *et al*., 1989; Szabolcs, 1994). Two major approaches have been proposed and employed to minimize deleterious effects of high soil/water salinity (Epstein *et al*., 1980). A technological approach of implementing large engineering schemes for reclamation, drainage, and irrigation with high quality water has been used effectively. Although this approach has been successful in some areas, the associated costs are high, and it often provides only a temporary solution to salinity problems. The second approach, which must be implemented in conjunction with the first, entails biological strategies focused on the exploitation or development of plants capable of tolerating high soil/water salinity. This approach includes diversifying cropping systems to include crops that are known to be salt tolerant (e.g., by crop substitution), exploiting wild or feral species that are adapted to saline environments (e.g., by domestication), and genetically modifying domesticated crops by breeding and selection for improved salt tolerance. Crop substitution has been largely practiced since the beginning of agriculture, and is one of the most practical strategies to deal with salinity when growing field crops (Shannon, 1996). However, this method is practically limited because, for many crop plants, including most vegetables, often no alternative salt-tolerant genotype can be found within the cultigen. Therefore, the idea of developing salt-tolerant crops, through the use of traditional protocols of plant breeding or contemporary techniques of gene transfer, has gained significant ground.

Considerable efforts have been devoted to developing salt-tolerant lines or cultivars of various crop species using traditional plant breeding protocols. However, due to various difficulties, including complexities of the tolerance traits, lack of efficient selection criteria, and time- and labor-consuming procedures, rather limited progress has been made in developing or releasing salt-tolerant cultivars in any crop species (Ashraf, 1994; Ashraf and McNeilly, 2004; Flowers and Yeo, 1995; Shannon and Grieve, 1999). More recently, however, molecular biology and genetic engineering approaches have been proposed as an alternative, and may provide faster methods for developing salt-tolerant plant genotypes. Although such approaches have contributed significantly to our understanding of the genetic controls of salt tolerance at the molecular and cellular levels, thus far only limited progress has been made in developing transgenic plants with improved salt tolerance. This is in part due to the fact that plant response to

salinity is different at different levels of organization, including cell, tissue, organ, and whole plant, and also that, at each level, different sets of genes might be involved (Ashraf, 2002; Quesada *et al*., 2002). Complex interactions between salt stress and various molecular, biochemical, and physiological phenomena may affect plant growth and development under salt stress (Zhu, 2002). Furthermore, the effect of one mechanism may mutually exclude the effect of others at certain stages of plant development (Carvajal *et al*., 1999). However, as we gain a better understanding of the complex mechanisms involved in plant salt tolerance, the transgenic approach may find more utility for developing salt-tolerant cultivars. Nonetheless, agriculturists can employ alternative approaches to alleviate adverse effects of salt stress on plants at different developmental stages. One approach involves treatment of seed with different inorganic or organic chemicals and/or with high or low temperatures to improve germination, early seedling growth, and final crop yield under salt stress, as discussed in this chapter.

For the first time, Strogonov (1964) proposed that salt tolerance of plants could be enhanced by treatment of seed with salt solution prior to sowing. Such controlled imbibition of seed followed by dehydration, also referred to as ''seed priming,'' was shown to improve germination and early seedling growth under salt stress compared to plants grown from untreated seed. During priming, seed are generally exposed to an external water potential that is low enough to prevent germination but allows some pre-germinative physiological and biochemical processes to take place (Bradford, 1986). Primed seed would then germinate more rapidly than unprimed seed when placed in an appropriate germination environment. Rapid seed germination and uniform field emergence are essential to the establishment of successful crops under both saline and non-saline conditions. Slow or sporadic germination and emergence generally result in fewer and smaller plants, which are more vulnerable to different biotic and abiotic stresses. A prolonged emergence period may also lead to deterioration of the seed bed and increased soil compaction, which may result in poor stand establishment. Over the past two decades, seed priming has become a common practice to increase the rate and uniformity of field germination and emergence in many important crop plants.

Various prehydration or priming treatments have been employed to increase the speed and synchrony of seed germination (Bradford, 1986). Common priming techniques include osmopriming (soaking seed in osmotic solutions such as PEG), halopriming (soaking seed in salt solutions), hydropriming (soaking seed in water), matric priming (treating seed with a solid matrix), thermopriming (treating seed with low or high temperatures), and priming with plant growth hormones. Also, when seed are coated

with bacteria and soaked in warm water until their moisture content rises to 35–40%, the term "biopriming" is used. Generally, any type of priming would cause an effective invigoration of the dry seed, which is the inception of metabolic processes that normally occur during imbibition and which are subsequently fixed by drying the seed (Heydecker and Coolbear, 1978). Haigh (1988) reported that in tomato (*Lycopersicon esculentum*), priming resulted in more rapid imbibition, increased the extensibility of radicle cell walls, and weakened the endosperm, which together shortened the lag phase between imbibition and radicle emergence.

In this chapter, we have evaluated, discussed, and compared the effectiveness of different priming techniques for enhancing seed germination, seedling emergence, and crop performance under non-saline and saline conditions in different species. We also have discussed physiological and biochemical processes involved in seed priming.

II. OSMOPRIMING

Osmopriming, also known as osmoconditioning or osmotic conditioning, refers to soaking seed in solutions of sugars, polyethylene glycol (PEG), glycerol, sorbitol, or mannitol, followed by drying the seed before sowing. The low water potential of the treatment solution allows partial seed hydration so that pre-germination metabolic processes begin but germination is inhibited (Bennett *et al*., 1992; McDonald, 2000; Pill and Necker, 2001). When the primed seed are planted in the field, they usually exhibit rapid and uniform germination.

A. Effect of Osmopriming on Seed Germination and Seedling Emergence

Osmopriming contributes to significant improvement in seed germination and seedling growth in different plant species grown under saline conditions. For example, seeds of tomato and asparagus (*Asparagus officinalis*) osmoconditioned in -0.8 MPa PEG-8000 showed increased germination under saline media (Pill *et al*., 1991). Similarly, osmoconditioning of Bermuda grass (*Cynodon dactylon*) seed using PEG followed by immediate sowing improved germination and seedling growth under saline conditions (Al-Humaid, 2002). Osmoconditioning of cucumber (*Cucumis sativus*) seed with 0.7 M mannitol improved the rate of germination at 25 and 15°C in water and NaCl solutions of up to 200 mM (Passam and Kakouriotis, 1994).

In the latter study, osmoconditioning also promoted the rates of radicle extension, seedling emergence, and expansion of the cotyledons and the first leaf of cucumber.

B. Effect of Osmopriming on Seed Structure and Biochemistry

A number of ultra-structural and biochemical changes have been reported in osmo-primed seeds of different plant species. In tomato, for instance, a space is developed in the primed seed that facilitates water uptake, thereby accelerating the speed of germination (Argerich and Bradford, 1989). Also, during priming, the embryo expands considerably and compresses the endosperm, deforming the tissues that have lost flexibility due to dehydration (Liptay and Zariffa, 1993). This produces free space, which in turn facilitates root protrusion after rehydration (Lin *et al*., 1993). It has been proposed that priming causes considerable invigoration of the dry seed (Heydecker and Coolbear, 1978), which results from the initiation of metabolic processes that normally take place during imbibition and are fixed by subsequent drying (Hanson, 1973). In pea (*Pisum sativum*) seed, for example, priming prevented some of the chromosomal damages resulting from aging or repaired age-induced genetic damages (Sivritepe and Dourado, 1995). Priming also has been shown to induce nuclear DNA synthesis in the radicle tip cells in tomato (Liu *et al*., 1997) and several other plant species, including pepper (*Capsicum annuum*) (Lanteri *et al*., 1993a; Lanteri *et al*., 1993b), maize (*Zea mays*) (Garcia *et al*., 1995), and leek (Ashraf and Bray, 1993; Clark and James, 1991).

Osmopriming has been shown to activate processes related to cell cycle. For example, priming tomato seed induced the expression of ß-tubulin, which plays an important role in cell cycle (de Castro *et al*., 1995). Using flow cytometric analyses of the nuclear DNA content, Özbingöl *et al*. (1999) examined the effect of osmopriming on activation of cell cycle in embryo root tips of tomato seed. In dry untreated seed, ~91% of the nuclei revealed 2C signals. Priming the seed in PEG-8000 improved the germination rate, which was also associated with an increase in 4C signals. The results revealed a positive linear relationship between frequency of 4C DNA nuclei (or the 4C/2C ratio) and the positive effect of priming. In a different study, cell cycle events in embryo of tomato seed were examined during imbibition in water and during osmoconditioning using both quantitative and cytological analysis of DNA synthesis and ß-tubulin accumulation (de Castro *et al*., 2000). It was determined that most embryonic nuclei of dry, untreated seed were arrested in the G_1 phase of the cell cycle, which was ascribed to the absence of DNA synthesis (the S-phase). In addition,

ß-tubulin was not detected on western blots, and microtubules were not present. During imbibition in water, DNA synthesis was activated in the radicle tip and spread toward the cotyledons, resulting in an increase in the number of nuclei in the G_2 stage. In addition, ß-tubulin was accumulated and assembled into microtubular cytoskeleton networks. Both of these events preceded cell expansion and division and subsequent growth of the radicle through the seed coat. When seed were osmoconditioned, the activation of DNA synthesis and the formation of microtubular cytoskeleton networks were observed throughout the embryo; however, this pre-activation of the cell cycle appeared to be arrested in the G_2 phase, as no mitosis was observed. The pre-activation of cell cycle events in osmoconditioned seed appeared to be correlated with the enhanced germination performance of the primed seed (de Castro *et al*., 2000). In comparison, Gurushinghe *et al*. (1999) reported that while in some tomato seed lots the percentage of 4C nuclei in the radicle meristems prior to emergence increased in proportion to accumulated hydrothermal priming time, in others no increase in nuclear DNA content was detected. All seed lots, however, demonstrated rapid radicle emergence following priming. Thus, although often an increase in DNA synthesis in radicle meristem nuclei occurred during seed priming, such an increase was not essential for germination advancement.

Water uptake and its subsequent cell-to-cell movement during germination were suggested to be controlled by aquaporins, integral membrane proteins that form water channels (Chrispeels and Maurel, 1994). If so, it is likely that priming induces the expression of aquaporins, resulting in increased germination under stress conditions. Gao *et al*. (1999) studied plasma and tonoplast membranes' aquaporins in osmoconditioned seed of oilseed rape (*Brassica napus*) during germination under both salt and osmotic stresses and isolated two aquaporin genes from a cDNA library. It was determined that the first gene, *Bn-PIP1* of 1094 bp, encoding a putative polypeptide of 287 amino acids with a predicted molecular mass of 30.4 kDa and pI of 7.8, belonged to the family of plasma membrane intrinsic protein (PIPs) aquaporins. The second gene, *Bn-TIP2* of 1020 bp, encoded a putative polypeptide of 253 amino acids with a predicted molecular mass of 25.8 kDa and pI of 5.8. It was further determined that the transcripts of both *Bn-PIP1* and *Bn-TIP2* were present earlier during germination in primed seed than in unprimed seed. However, it was suggested that *Bn-PIP1* was related to water transportation required for enzymatic metabolism of storage reserves at early stages of germination, whereas *Bn-TIP2* expression was related to cell growth associated with radicle protrusion. While seed priming induced the expression of *Bn-PIP1*, it did not have any effect on the expression of *Bn-TIP2*.

Osmopriming may contribute to rapid seed germination by affecting active oxygen metabolism. In wild rye (*Leymus chinensis*) seed, for example, priming with 30% PEG for 24 h resulted in increases in the activity of superoxide dismutase (SOD) and peroxidase (POD) and a rapid increase in the respiratory intensity, which were associated with an increase in germination vigor (Jie *et al*., 2002). Osmopriming may also contribute to rapid seed germination by reducing the mechanical restraint of endosperm on developing embryo (Mayer and Poljakoff-Mayber, 1989). For example, it was determined that osmotic priming of tomato seed increased the endo-beta-mannanase activity in the endosperm cap and decreased its mechanical restraint on the germinating embryo (Toorop *et al*., 1998). A strong correlation was observed between lowering of the mechanical restraint and the activity of endo-beta-mannanase. Similarly, in osmoconditioned seed of lettuce (*Lactuca sativa* L.), endo-beta-mannanase activity persisted in primed seed following seed drying, and it was detected before radicle protrusion (Nascimento *et al*., 2001).

C. Effect of Osmopriming on Enzyme Activities in the Germinating Seed

Enzymes such as amylases, proteases, and in some cases, lipases, play vital roles in the early growth and development of embryo. Any increase in the activity of these enzymes may result in early vigorous growth and good crop establishment. It has been demonstrated that osmopriming affects the activity of these enzymes in the germinating seed of different plant species. For example, in muskmelon (*Cucumis melo*), seed osmoconditioned with PEG-6000 showed enhanced activity of dehydrogenase and amylase and improved germination under non-saline conditions (Singh *et al*., 1999). In oilseed crops, the glyoxylate pathway, which converts lipids into sugars, plays an important role in the early development of embryo (Taiz and Zeiger, 2002). Up- or down-regulation of any of the enzymes involved in this pathway may affect embryo growth. For example, it was determined that osmoconditioning increased the activity of isocitrate lyase, a key enzyme of glyoxylate pathway, in the germinating seed of peanut (*Arachis hypogaea*) (Fu *et al*., 1988). Osmoconditioning also enhanced the activity of ATPase in the germinating seed of peanut primed with PEG. Furthermore, acid phosphatase and RNA syntheses were significantly higher in embryonic axes and cotyledons of osmoconditioned seed compared to control seed. Thus, osmopriming may contribute to improved germination rate in part by increasing various enzyme activities.

D. Effect of Osmopriming on Organic Substances in the Germinating Seed

In most seeds, the storage organs usually contain substantial amounts of at least two of four major storage reserves (carbohydrates, lipids, proteins, and phosphorus-containing compounds), which degrade concurrently during germination (Bewley and Black, 1994). Mobilization of these reserves is essential for the growth and development of the embryo. Osmotic priming of the seed may alter the rate of storage mobilization. In sugarbeet (*Beta vulgaris*) seed, the relationship between initial mobilization of 11-S globulin storage protein and germination performance after osmopriming in −2.0 MPa PEG-8000 was studied (Capron *et al*., 2000). Priming was conducted for 2 d at various temperatures (5–40 °C) and atmospheric oxygen concentrations (0–21%). The range of temperatures and concentrations of oxygen that were effective in priming were also similar to those suitable for solubilization of the B-subunit of 11-S globulin. This finding suggested the usefulness of this protein marker for optimization of sugarbeet seed priming. In the same study, an osmopriming period longer than 2 d resulted in a remarkable decrease in germination. For instance, after a 14-day osmopriming at 25 °C, as much as 60% of the seed population failed to germinate when transferred to water. This loss in germination performance was ascribed to the degradation of late embryogenesis abundant (LEA) proteins, specifically a heat-stable seed-specific protein of about 60 kDa and a seed-specific biotinylated LEA protein. In another study with the same species, Bourgne *et al*. (2000) measured the soluble and total B-subunit contents of untreated and primed sugarbeet seed using a sensitive single-seed ELISA. They discovered a 160-fold range in the soluble B-subunit content among individual untreated seed, and only about a 5-fold range in osmoprimed seed. Furthermore, the primed seed population exhibited a substantially higher value of total B-subunit content than the untreated population. In a different study, Fu *et al*. (1988) determined that soaking peanut (*Arachis hypogaea*) seed in 20–25% PEG for 48 h greatly increased phosphate uptake and RNA synthesis in embryonic axes while improving seed vigor. Simultaneously, membrane permeability decreased and index of unsaturated fatty acid increased as seed vigor increased. Furthermore, PEG osmopriming resulted in increases in ethylene release, 1-amino-cyclopropane-carboxylic acid (ACC) content, and ACC synthetase activity. Experiments with mannitol-osmoconditioned seed of white cabbage (*Agrostemma githago*) showed a promotive effect on protein, RNA, and especially DNA synthesis (Koehler *et al*., 1995). However, two-dimensional separation of soluble proteins did not verify dramatic changes in the protein pattern of osmoconditioned seed. From the above-mentioned studies, it is evident that although considerable

changes take place in organic storage reserves in the seed due to osmoconditioning, the extent and nature of these changes may vary from species to species. This could be due in part to the time period and concentration of osmoticum to which seed were subjected before sowing.

E. Effect of Osmopriming on Later Plant Growth and Metabolism

Osmotic priming to improve seed germination performance may also enhance general crop performance. For example, priming chickpea (*Cicer arietinum*) seed with either 4% mannitol or water for 24 h improved crop performance under field conditions, compared to a control crop based on non-primed seed (Kaur *et al.*, 2002). Specifically, while the average seed yield per plant was 3.6 g in the control crop, it was 5.0 or 5.9 g in the water- or mannitol-primed crops, respectively, showing an increase of 39 or 64%. In a study with Turkish pine (*Pinus brutia*) var. eldarica, Khalil *et al.* (1997) determined that plants raised from seed preconditioned at room temperature in aerated solution of PEG-8000 for different time periods exhibited faster germination and higher shoot length and dry weight compared to plants raised from untreated seed. The best treatments were priming seed with PEG concentration of 200 or 300 g/kg water for 9 d. Similarly, osmoconditioning of Italian ryegrass (*Lolium multiflorum*) and sorghum (*Sorghum bicolor*) seeds with 20% PEG-8000 for 2 d at 10°C increased percent germination, germination rate, seedling establishment, and dry matter production under water-stressed, waterlogged, cold-stress, or saline conditions (Hur, 1991). In cucumber, osmoconditioning of seed using 0.7 *M* mannitol in darkness at 25°C for 3 d improved the rate of germination, radicle extension, seedling emergence, and expansion of first leaf, but did not have any significant effect on growth rate of the second leaf or photosynthetic activity of either the first or the second leaf (Passam and Kakouriotis, 1994). In spite of many reports of the positive effects of osmopriming on plant growth and development, there is also research evidence that disagrees. For example, osmoconditioning of soybean (*Glycine max*) seed produced variable results; while priming with mannitol did not alter field emergence, priming with PEG promoted rapid and uniform emergence in early plantings (Helsel *et al.*, 1986). However, once the stand was established, other environmental and growth factors promoted or inhibited yield expression. Similarly, no significant effect was observed on one-month-old neem (*Azadirachta indica*) plants raised from seed osmoconditioned with different concentrations of PEG-6000 (Vanangamudi *et al.*, 2000). In view of these reports, it is evident that considerable gain

in terms of growth and seed yield may be achieved in many crops through osmopriming.

III. HALOPRIMING

Halopriming is defined as soaking seed in varying concentrations of inorganic salts. This pre-conditioning is particularly used when sowing seed in salt-afflicted soils. Various studies indicate considerable improvement in seed germination, seedling emergence and establishment, and final crop yield in salt-affected soils as a result of seed halopriming.

A. Effect of Halopriming on Seed Germination and Seedling Emergence

In the past two decades, intensive research has been conducted to improve seed germination and seedling emergence under saline conditions by pre-treating seed with solutions of different inorganic salts. For example, it was determined that rice seed treated with mixed salt solution germinated significantly more rapidly than unprimed seed under salt-stress conditions (Chang-Zheng *et al*., 2002). Similarly, presoaking *Echinacea purpurea* seed in either 0.1% $MnSO_4$ or 0.05% $ZnSO_4$ solution resulted in increased germination percentage by 36 or 38% and increased laboratory germination frequencies to 89 or 91%, respectively (Babaeva *et al*., 1999). Field emergence was also increased by 27–41%. Despite these results, there are some reports suggesting the absence of any halopriming effect on germination under saline conditions. For example, pretreatment of seed of a salt-tolerant and a salt-sensitive cultivar of spring wheat (*Triticum aestivum*) with either distilled water for 4–12 h or varying concentrations of KCl, KNO_3, $CaCl_2.2H_2O$ or $Ca(NO_3)_2.4H_2O$ did not improve germination rate in saline medium (Ashraf and Iram, 2002). Also, among the different salts used for priming, KNO_3 and KCl had inhibitory effects on initial growth of both cultivars. Similarly, seed of *Zoysia japonica* treated with 2% KNO_3 did not show any improvement in germination under non-saline conditions (Yan-Rong and Yan-Jun, 1997), and cotton (*Gossypium hirsutum*) seed primed with 10–60 mmol/liter $CaCl_2$ exhibited decreased germination and seedling emergence under NaCl treatment, with the degree of inhibition increasing with increased concentration of the treatment chemical (Xiao-Fang *et al*., 2000). The overall evidence indicates that while halopriming can improve seed germination and seedling

emergence in some plant species, it does not do so in all species. Further investigation is needed to determine the effects of halopriming on seed germination and seedling emergence in a larger array of plant species.

B. Effect of Halopriming on Enzyme Activities in the Germinating Seed

Relatively few and small chemical changes are observed in dry seed; however, many changes occur in the seed immediately after rehydration (Bewley and Black, 1994). Of these, changes in activity of enzymes involved in hydrolysis of storage products play important roles in the initial growth and development of the embryo. Priming seed with inorganic salts may significantly alter activity of enzymes in germinating seed. For example, seed of muskmelon soaked with KNO_3 solution showed enhanced activity of dehydrogenase and α-amylase under low temperature (Singh *et al*., 1999). In untreated wheat seed germinating under salt stress, amylase activity decreased with increasing salinity; in wheat seed pretreated with $CaCl_2$, the negative effect of salinity was diminished (Roy and Srivastava, 1999). Similarly, in *Pennisetum americanum* and *Sorghum bicolor* seeds soaked in $CaCl_2$ or KNO_3 solution, activity of total amylase, α-amylase, and proteinases was increased in germinating seeds under salt stress (Kadiri and Hussaini, 1999). And in rice, seed primed with mixed-salt solution resulted in significant increases in activity of α-amylase, β-amylase, and root dehydrogenase, and moderate increase in the activity of shoot catalase under salt stress (Chang-Zheng *et al*., 2002). Such increases in enzyme activity have direct or indirect effects on subsequent seed germination and seedling growth and development.

C. Effect of Halopriming on Organic Substances in the Germinating Seed

Mobilization of seed food reserves to the developing embryo during germination is a ubiquitous process. Storage products such as carbohydrates, amino acids, fatty acids, and inorganic nutrients are mobilized in germinating seed at varying rates in different species (Bewley and Black, 1994). However, such mobilization may be perturbed when germinating seed are subjected to unfavorable environmental conditions such as soil salinity (Ashraf *et al*., 2003b). The extent of this perturbation is determined by the level of activity of enzymes involved in hydrolysis of storage chemicals. However, as indicated in the previous section, priming seed with inorganic salts would increase activity of most of the enzymes involved in seed germination, and

thus contribute to mobilization of organic substances to different parts of the embryo. In pigeonpea (*Cajanus cajan*), for example, seed treated with KNO_3 or $CaCl_2$ generally exhibited improvement in proteins, free amino acids, and soluble sugars during germinating under salt stress (Jyotsna and Srivastava, 1998). Similarly, melon (*Cucumis melo*) seed primed with 18 dS m^{-1} NaCl solution for 3 d at 20°C exhibited high accumulation of total sugar and proline during germinating (Sivritepe *et al*., 2003). However, because the information on the effect of halopriming on the mobilization of seed organic reserves is yet insufficient, no conclusion can be drawn as to the extent of the regulation of mobilization of organic substances during germination. Further studies are required to elucidate this phenomenon.

D. Effect of Halopriming on Inorganic Nutrients in the Germinating Seed

Salinity interacts not only with organic substances but also with inorganic nutrients in the plant. For instance, in corn seedlings grown under salt stress, mesocotyl retained Na^+ and restricted its translocation to the plumule (Johanson and Cheeseman, 1983). In wheat embryo, a marked decrease in K^+ level was observed under salt stress (Petruzzelli *et al*., 1991). Furthermore, it has been widely reported that Ca^{2+} and K^+ are decreased in plants under saline conditions (Ashraf and Rauf, 2001; Kent and Läuchli, 1985). However, increasing Ca^{2+} and K^+ concentrations in seeds of wheat (Idris and Aslam, 1975) and wimmera ryegrass (*Lolium rigidum*) (Marcar, 1986) improved germination under salt stress. In contrast, in pea, treatment of seed with Ca^{2+} or K^+ salt did not significantly improve final germination compared to treatment with distilled water (Guerrier and Pinel, 1989). In another study, while treatment of wheat kernel with 5% KH_2PO_4 solution increased germination percentage, accelerated seedling emergence, and increased uptake of N, P and K by seedlings, treatment with 0.25% $CaCl_2$, 2.5% NaCl, or $Ca(OH)_2$ saturated solution was not effective (Bhati and Rathore, 1986). In the same species, Kamboh *et al*. (2000) determined that treating seed of a salt-sensitive and a salt-tolerant variety with distilled water or 10 or 50 mM concentration of KCl, KNO_3, $CaCl_2$, or $Ca(NO_3)_2$ did not improve germination of either of the two cultivars. However, every treatment had a significant effect on improving shoot growth during early seedling establishment, especially in the salt-sensitive variety. Also, there were significant differences in the Ca^{2+} content of seed after various pre-sowing treatments and significant differences between the two varieties in the ion contents after seed treatment. The latter differences, however, appeared to be related to the improvement in shoot growth during early seedling establishment and not to pre-sowing seed treatments. In maize,

Ashraf and Rauf (2001) determined that concentrations of Na^+, K^+, and Ca^{2+} increased significantly in all parts of germinating seed primed with NaCl, KCl, or $CaCl_2.2H_2O$, respectively. In addition, seed primed with $CaCl_2.2H_2O$ were highest in Cl^- accumulation in all parts of the germinating seed, followed by seed treated with NaCl and KCl. Most of the Ca^{2+} was retained in the seed and mesocotyl and thus, its transport to plumules and radicles was restricted. All of these reports indicate that priming seed with solutions of inorganic salts affects the uptake of different inorganic nutrients differently in different parts of germinating haloprimed seed. However, the extent to which halopriming can restrict the uptake of toxic ions such as Na^+ and Cl^- in various growing parts of the embryo, particularly under saline conditions, is not yet fully elucidated. Limited uptake of these toxic ions is one of the most important phenomena associated with salt tolerance of most mesophytes, and further investigation in this area is warranted.

E. Effect of Halopriming on Later Plant Growth and Metabolism

Pre-sowing treatment with inorganic salts not only may promote seed germination, but also may stimulate subsequent growth and metabolic processes and enhance final crop yield (Eleiwa, 1989; Sallam, 1999). For example, wheat grain yield under saline conditions was improved by pre-soaking seed in different inorganic salts; soaking in $CaCl_2$ was more effective than soaking in NaCl, and soaking in 3% Na_2SO_4 was the most effective treatment (Mehta *et al.*, 1979). Presoaking of broad bean (*Vicia faba*) seed in KCl or NaCl solutions resulted in significant increases in growth parameters and concentrations of certain compounds such as sucrose, non-reducing sugars, carbohydrate, ribonucleic acids, and K^+ in the shoot (Sallam, 1999). Pretreatment of soybean seed with 0.25 M $CaCl_2$ for 24 h resulted in plants with increased seed number and reduced number of seedless pods, although it did not affect 100-seed weight (Eleiwa, 1989). This was coupled with an increase in N and decrease in Mn^{2+}, Fe^{2+}, Mg^{2+}, Ca^{2+}, K^+, and Na^+ contents in immature seed. Furthermore, the fat and protein contents were increased and the carbohydrate content decreased in the seed. In cotton, soaking seed in superphosphate solution increased the number of open bolls as well as seed yield per plant. In *Pennisetum americanum* and sorghum (*Sorghum bicolor*), plants raised from seeds treated with 100 mg/liter solution of $CaCl_2$ or KNO_3 had increased plant height, chlorophyll content, and yield compared to plants raised from untreated seeds (Kadiri and Hussaini, 1999). Similarly, wheat kernels treated with salt solution mixtures of NaCl, $CaCl_2$, and Na_2SO_4 (7:2:1) with varying concentrations of 0.35 (control), 4, 8, 12, and 16 dS m^{-1} resulted in plants exhibiting

significant increases in total chlorophyll, chlorophylls *a* and *b*, and chlorophyll *a:b* ratio compared to plants raised from untreated kernels (Roy and Srivastava, 2000).

Although considerable improvement in germination and later growth stages has been observed in different crop species in response to halopriming, for each plant species, the optimal salt composition and concentration and period of incubation (soaking) need to be determined. Similar treatments may have different results in different plant species. For example, while priming of pearl millet (*Pennisetum glaucum*) seed with NaCl exacerbated the adverse effect of salt stress on germination and later vegetative growth stages (Ashraf and Iram, 2002), similar treatment in tomato improved germination and seedling emergence under salt stress (Cayuela *et al*., 1996). Similarly, it was determined that in *Atriplex* species, priming with NaCl improved seed performance more than priming with iso-osmotic PEG solution (Katembe *et al*., 1998). The length of pretreatment (soaking) may depend on the hardness and thickness of the seed coat. For example, seed of cotton may require more time for effective priming than that of rice or wheat. Similarly, the specific temperatures at which seed are kept during priming or dried after priming are also important determinants of effective priming. Optimization of priming treatments would certainly involve a lot of time and labor, but it might be essential to determine the most effective and economic treatment for commercial application. Furthermore, mechanisms by which different components of priming solutions are taken up by the seed, processes that are subsequently incepted or activated in different parts of the seed, and nature of interactions among different nutrients within the seed should be elucidated to facilitate practical application of seed priming in crop production.

IV. HYDROPRIMING

In many agricultural areas, a major cause of poor stand establishment and low crop yield is unfavorable environmental conditions for seed germination and seedling emergence. However, rapidly germinating seedlings could emerge and produce deep roots before the upper layers of the soil are dried out and crusted, which may result in good crop establishment and higher crop yield. Any factor that facilitates rapid germination may contribute to establishment of a successful crop. A low-cost approach, designated as "on farm seed priming," was proposed by Harris (1992), and involved soaking of seed in water before sowing. This presowing seed treatment, known as hydropriming, allows the seed to imbibe water and go through the first phase of germination in which pre-germination metabolic activities

are preceded while the latter two phases of germination are inhibited (Pill and Necker, 2001).

Although soaking seed in water and drying before sowing is the easiest way to achieve hydration, a major disadvantage is that it may result in uneven hydration and non-uniform germination (Pill and Necker, 2001). Also, soaking is not suitable for some plant species, as rapid hydration may cause leakage of essential nutrients out of the seed, resulting in seed damage. To overcome these potential problems, various methods have been devised to deliver appropriate hydration to the seed. One method is seed humidification – a presowing treatment in which seed are equilibrated under conditions of high humidity (Finnerty *et al*., 1992; Suzuki and Khan, 2001). For example, in partially-aged mustard (*Brassicajuncea)* seed, humidification resulted in a significant improvement in germination and seedling vigor and a decrease in leakage of electrolytes from germinating seed (Srinivasan *et al*., 1999). In snap beans (*Phaseolus vulgaris*), humidification resulted in improved germination, ACC-derived ethylene production, and seedling emergence and growth (Suzuki and Khan, 2001).

A second method of presowing seed hydration is aerated hydration (AH), in which seed are hydrated in a column of aerated water to a moisture content close to that required for radicle protrusion (Thornton and Powell, 1992). Seed are held inside the column at this moisture content, and subsequently are removed and dried before radicle protrusion occurs. Thornton and Powell (1992) determined that for seeds of cauliflower (*Brassica oleracea*) and Brussels sprouts (*Brassica oleracea*), an 8-h AH treatment at 25°C was the most effective for improving the rate and uniformity of germination, root growth, and seed vigor. In a different study on the same species, additional improvements in seed vigor were obtained by AH for up to 32 h at 20°C (Thornton and Powell, 1995). Similar improvement in seed quality due to AH was also observed in oilseed rape (Powell *et al*., 1993). The overall research results suggest that activation of metabolic repair phenomena is a major contributor to improvements achieved by AH. For example, in *Brassica* seed, activation of DNA repair synthesis was shown to occur during AH (Thornton *et al*., 1993).

A. Effect of Hydropriming on Seed Germination and Seedling Emergence

Similar to other priming techniques, hydropriming generally enhances seed germination and seedling emergence under both saline and non-saline conditions, although there are exceptions. For example, while Roy and Srivastava (1999) reported that soaking wheat kernels in water improved their germination rate under saline conditions, no such improvement was

obtained in similar research conducted by Ashraf and Iram (2002). Yet hydropriming improved salt tolerance of maize (Ashraf and Rauf, 2001) and pigeonpea seeds (Jyotsna and Srivastava, 1998). However, more research is needed to determine the value of hydropriming in different plant species.

B. Effect of Hydropriming on Enzyme Activities in the Germinating Seed

In seed of some plant species, trypsin-like proteolytic enzymes, which are produced during seed development, are important during germination. The activity of such enzymes, however, is often prevented by trypsin inhibitors, which may be present in the seed and play regulatory roles in protein mobilization during germination (Bewley and Black, 1994). Priming, however, may reduce the inhibitory activities of such enzymes and promote germination. For example, in sorghum, soaking seed in distilled water or salt solution reduced inhibitory activities of trypsin and chymotrypsin, although the effect of the latter treatment was greater (Mulimani and Vadiraj, 1994). Similar results were obtained when seed of red gram (*Cajanus cajan*) were pre-soaked in distilled water or salt solution (Mulimani and Paramjyothi, 1995).

Amylases are key enzymes that play a vital role in hydrolyzing the seed's starch reserve, thereby supplying sugars to the developing embryo. Effects of hydropriming on water potential, the driving force for water uptake during imbibition, and the activity of α-amylase were examined in wheat and rice kernels (Andoh and Kobata, 2002). At the time of sowing, while water and osmotic potentials of hydroprimed wheat seed were −7.2 and −12.3 MPa, respectively, they were −4.8 and −9.9 MPa in the non-primed seed. In rice seed, hydropriming did not change either water or osmotic potential. In primed seeds of both wheat and barley (*Hordeum vulgare*), however, the activity of α-amylase at 12 h after sowing was, respectively, 2.7 and 2.8 times greater than that in non-primed seeds. The primed seeds also exhibited a faster rate of germination and seedling emergence. The authors concluded that improvements in seed germination and seedling emergence were due to enhanced supply of soluble carbohydrates to the growing embryo, which was caused by an increase in α-amylase activity. The authors further speculated that redrying of seed following hydropriming did maintain activity of other enzymes at the levels required for occurrence of germination. In a different study, it was determined that hydropriming mitigated the adverse effect of salinity on amylase activity in wheat kernel (Roy and Srivastava, 1999). Thus, hydropriming may have significant beneficial effects on enzyme activity required for rapid seed germination.

C. Effect of Hydropriming on Organic and Inorganic Substances in the Germinating Seed

Presoaking of seed in water may alter the mobilization of both inorganic and organic substances from the storage organs to the developing embryo in some species. In sugarbeet, for example, it was determined that the effect of hydropriming on improving seed germination was closely related to the solubilization of β-subunit of 11-S globulin storage protein (Capron *et al.*, 2000). Similarly, in pigeonpea, hydropriming was determined to be very effective in the mobilization of compounds such as proteins, free amino acids, and soluble sugars from storage organs to growing embryonic tissues under salt stress (Jyotsna and Srivastava, 1998). In contrast, lipid composition of Korean black soybean (*Glycine max*) seed, including percentages of neutral fats, glycolipids, and phospholipids, was determined to remain unchanged after soaking in water (Oh *et al.*, 1992). Also, while soaking did not affect major components of neutral fats and glycolipids, a slight change was observed in some components of phospholipids. However, in view of these contrasting reports, it is not possible to draw any strict parallels between mobilization of different inorganic or organic substances due to hydropriming and improved germination. It is likely that the extent of mobilization of these substances depends on plant species and time period for which seed are subjected to water redrying and sowing.

D. Effect of Hydropriming on Later Plant Growth and Metabolism

A review of the relevant literature suggests that hydropriming of seed has growth-promoting effects on plants at the initial and later developmental stages. Promoting effects at later stages can be due to alteration in various metabolic phenomena responsible for enhanced yield. In field experiments, hydropriming of safflower (*Carthamus tinctorius*) seed for 12 h resulted in higher number of plants/m^2, capitula per plant, grains per capitulum, 1000-seed weight, grain yield, and oil content compared to untreated seed (Bastia *et al.*, 1999). Similar improvements were observed in maize, rice, chickpea (Harris *et al.*, 1999), and pearl millet (Kumar *et al.*, 2002) grown under dryland conditions. The latter authors also determined safe maximum lengths of time for which seed should be primed, beyond which it could be damaging to the seed or seedling. Recommended safe limits were 24 h for maize and rice, 10 h for chickpeas, and 8 h for pearl millet.

In addition to improvement in crop yield, hydropriming may cause marked changes in some biochemicals in later plant growth stages. For example, in a greenhouse pot experiment, Sallam (1999) demonstrated that

while plants of *Vicia faba* raised from water-soaked seed exhibited significantly higher growth than those raised from untreated seed under saline conditions, hydropriming also eliminated the adverse effect of salinity on total and reducing sugars, lactose, maltose, and proline. Similarly, presoaking treatment of wheat kernel with water resulted in significant increases in total chlorophyll, chlorophylls a and b, and chlorophyll a:b ratio compared with untreated seed under salt stress (Roy and Srivastava, 2000).

Based on the limited number of reports available on this subject in the literature, it seems that hydropriming is effective in improving plant vegetative growth and seed yield in addition to causing considerable alterations in various metabolites responsible for enhanced growth of plants under saline or non-saline conditions. Some researchers have considered hydropriming a "key technology" that is simple and cost effective, the impact of which is very high in terms of enhanced yield (Harris *et al*., 1999).

V. MATRIC PRIMING

Matric priming, also known as matriconditioning or solid matrix priming (SMP), is a pre-sowing process in which a solid matrix, instead of an osmotic solution, is used to prime the seed and enhance germination. It involves the use of a mixture of solid matrix materials, water, and seed to control water, oxygen, and temperature effects on germination. The solid materials used possess many ideal characteristics such as low matric potential, negligible water solubility, high water-holding capacity, high surface area, non-toxicity, and ready adherence to the seed. Specialized vermiculite compounds (e.g., Zonolite), Celite, and Micro Cel E (primarily diatomaceous earth, hydrated lime, and water) are usually used, as they have high matric potential and low osmotic potential. The choice of materials (priming agents) used for SMP has significant effects on seed performance because of differences in pH and chemical compositions of priming agents. Solid-matrix primed seed are allowed to imbibe enough water to complete the pre-germination process but not enough to initiate radicle emergence. This situation is provided by reducing matric potential of the available water through adsorption on surface of the priming agents.

A. Effect of Matric Priming on Seed Germination and Emergence

Solid matrix priming has been highly effective in improving seed germination and seedling emergence in many plant species, including some vegetables (Khan *et al*., 1992; Khan *et al*., 1995), maize (Afzal *et al*., 2002; Podlaski *et al*.,

2002), sorghum and bean (Colon *et al*., 1995), Kentucky bluegrass (*Poa pratensis*) and tall fescue (*Festuca arundinacea*) (Pill *et al*., 1997), switchgrass (*Panicum virgatum*) (Madakadze *et al*., 2000), four fescue (*Festuca* spp.) species (Frett and Pill, 1995), hot pepper (Dabrowska *et al*., 2001), broccoli (Jett *et al*., 1995; Jett *et al*., 1996), and parsley (*Petroselinum crispum*) (Podlaski *et al*., 2003). In these studies, however, different priming agents, temperatures, and time periods were used for effective SMP in different species.

A comparison of the effectiveness of SMP in enhancing seed germination with other priming methods indicates that SMP may be a superior method. For example, Dabrowska *et al*. (2001) determined that while both SMP and osmopriming significantly increased the speed and capability of emergence and mean dry weight of hot pepper seedlings, SMP was more effective in improving seedling emergence. Using maize seed, Podlaski *et al*. (2002) determined that SMP was more effective than hydropriming in improving seedling emergence under field conditions. Similarly, Afzal *et al*. (2002) demonstrated that in maize kernels, priming with water (hydropriming) or PEG-10000 (osmopriming) was less effective than priming with compost, pressed mud, or gunny bags to enhance germination. Furthermore, SMP of seeds of four fescue species at −1.5 MPa and 20 °C for 4 d resulted in superior post-priming seed germination compared with priming in higher water potential of PEG or $NaNO_3$ (Frett and Pill, 1995). Superiority of the matriconditioning over osmoconditioning in enhancing seed germination was also demonstrated in parsley (Pill and Kilian, 2000) and Kentucky bluegrass (Pill and Korengel, 1997). Using broccoli seed, Jett *et al*. (1996) ascribed the superior germination performance of metrically primed seed to increased oxygen availability during priming, increased seed Ca^{2+} content, or improved membrane integrity.

B. Effect of Matric Priming on Seed Structure and Biochemistry

Remarkable ultrastructural changes have been observed in seed of different species after matric priming. For example, Dawidowicz-Grzegorzewska (1997b) observed that enhancement in germination of carrot (endospermic) and cucumber (non-endospermic) seeds primed with solid matrix Micro Cell E was due to degradation of storage protein and lipid bodies, followed by starch accumulation. In the endosperm tissue of carrot seed, the catabolic changes were restricted to the part enclosing the radicle, where partial degradation of storage protein bodies and complete degradation of storage cell wall components (polysaccharides) were observed (Dawidowicz-Grzegorzewska, 1997a). The breakdown of the storage materials in the endosperm (i.e., weakening of the endosperm), however, represented a secondary effect of SMP, which was probably controlled and stimulated by the metabolically advanced embryo. In another study with low-viable seed of cucumber, matriconditioning improved germination rate by stimulating hydrolysis of storage

protein bodies in the embryo, increasing dehydrogenase activity, ethylene production, and ACC oxidase activity, and decreasing electrolyte leakage (Habdas *et al*., 2000). Seed with a poor germination rate showed reduced enzyme activity and increased electrolyte leakage associated with cell damage and necrosis, growth of pathogenic fungus, and necrotization of whole seed. Results from the various studies indicate that matriconditioning is a useful method for improving the quality of aged seed, provided that seed deterioration has not gone too far.

C. Effect of Matric Priming on Enzyme Activities in the Germinating Seed

Similar to other priming systems, SMP also causes significant changes in the activity of enzymes involved in the hydrolysis of storage compounds as well as other enzymes in the seed. For example, in *Brassica parachinensis* seed, activity of catalase, superoxide dismutase, peroxidase, and acid phosphatase were increased in response to SMP (Xiao-Zhen and Jia-Rui, 1997). Similarly, in matriconditioned seed of hot pepper, enzymatic activity of dehydrogenases in embryo and endosperm were more than those in untreated seed (Dabrowska *et al*., 2001). In *Callistephus chinensis*, total dehydrogenase and *in vivo* ACC oxidase activity, as well as release of endogenous ethylene, increased in matriconditioned seed compared with untreated seed (Grzesik *et al*., 2000). In cucumber, matriconditioning improved germination rate by stimulating hydrolysis of storage protein bodies in the embryo and increasing dehydrogenase activity, ethylene production, and ACC oxidase activity, and decreasing electrolyte leakage (Habdas *et al*., 2000). In the same study, it was also determined that seed with the lowest germination percentage had reduced enzyme activity. In loblolly pine (*Pinus taeda*) seed, the increase in thiol proteases during priming paralleled degradation of proteins needed for germination and synthesis of new cell membranes (Wu *et al*., 1999). All these studies suggest that SMP has a promotive effect on activities of enzymes associated with pathways responsible for enhanced seed germination. However, whether the positive relationships drawn in the above-mentioned species are also true in other plant species is unknown. A larger number of species must be examined before such a generalization can be made.

D. Effect of Matric Priming on Organic Substances in the Germinating Seed

Matric priming causes considerable changes in organic storage substances in the seed of various species. For example, in loblolly pine it was determined that accumulation of most of the free amino acids increased in seed embryo after two days of SMP and remained high until the late stage of priming (Wu

et al., 1999, 2001). Of the different amino acids, proline level increased by 2.5 fold by the fourth day of SMP, and contributed to more than 50% of the osmotic adjustment generated by total amino acids. A consistent decrease in both water and osmotic potentials was also observed in the embryo during SMP. Furthermore, the contents of all free amino acids increased in the embryo four days after germination. In the same studies, pre-priming treatment of seed with thiol protease inhibitors (e.g., $CuCl_2$, $HgCl_2$) reduced the SMP effects on amino acid accumulation, osmotic adjustment, and enhancement of thiol protease activity. The results suggested that thiol protease might be induced by SMP and is involved in protein degradation and generation of free amino acids for osmotic adjustment and seed invigoration. In bitter gourd (*Momordica charantia*) seed primed with moistened vermiculite at 25° C for 36 h followed by air-drying to their initial moisture level showed marked increases in the activity of anti-oxidative enzymes and the levels of antioxidants (Wang *et al*., 2003). In the same species, the amounts of malondialdehyde (MDA) and total peroxide were reduced and the activity of several free radical and peroxide scavenging enzymes elevated in imbibing matriconditioned seed, compared to imbibing untreated seed (Hsu *et al*., 2003). The results suggested that improved germination could in part be due to a decrease in lipid peroxidation during imbibition and peroxide scavenging activity. In hot pepper, a significant change in protein metabolism was observed in response to SMP (Ilyas *et al*., 2002). The total protein extracted from matriconditioned seed was 16% higher than that from untreated seed. Prominent qualitative changes were also noted in the profiles of total proteins isolated from matriconditioned seed within the 76, 45, 38, 30 and 20 kDa polypeptides. Interestingly, an increase in organic metabolites such as proline and different antioxidants in germinating seed due to matric priming is parallel to what generally occurs in most salt-tolerant plants during later stages of growth under salt stress. Thus, matriconditioning may be an effective approach to improved salt tolerance of plants.

E. Effect of Matric Priming on Later Plant Growth and Metabolism

Matric priming is shown to promote growth during early and later stages of plant development and increase final crop yield in at least carrot (Szafirowska and Janas, 2000), maize (Afzal *et al*., 2002; Podlaski *et al*., 2002), hot pepper (Dabrowska *et al*., 2001) and broccoli (Jett *et al*., 1995). In hybrid maize, for example, following seed priming with water or solid substances, the increase in total dry biomass and kernel yield was 7–29% and 8–17%, respectively (Podlaski *et al*., 2002). However, how matriconditioning affects the physiological or biochemical processes responsible for improved growth and

yield is not known, although there are reports indicating changes in particular metabolites in adult plants raised from matriconditioned seed. For example, higher concentrations of carotenoids and capsaicin were found in fruit of hot pepper plants raised from matriconditioned seed, when compared to those raised from untreated seed (Dabrowska *et al*., 2001; Dabrowska *et al*., 2002).

VI. THERMOPRIMING

Similar to other stages of plant growth and development, seed germination is considerably affected by changes in external temperature. Optimum temperature requirements for seed germination may vary across species or even within species across genotypes. However, pre-sowing treatment of seed with low or high temperatures can positively affect the rate and final percentage of germination (Hardegree, 1996; Min and Seo, 1999). Thus, thermopriming is defined as pre-sowing seed treatment with low or high temperatures to improve germination and emergence under different environmental conditions. For example, in many species, germination may fail at high temperatures, a phenomenon known as thermoinhibition (Small and Gutterman, 1992). Various seed thermopriming treatments, including low- and high-temperature treatments, can be employed to mitigate thermoinhibition (Cantliffe, 1981). In agriculture, low-temperature treatment of seed is a routine practice in some species to either protect seed from precocious germination in inappropriate seasons or environments or to positively improve germination (Bewley and Black, 1994). Furthermore, pre-sowing thermopriming of seed may be used not only to improve seed germination and seedling emergence, but also to improve later plant growth and development, as discussed below.

A. Effect of Thermopriming on Seed Germination and Emergence

In many crop species, seed germination and emergence can be significantly improved by pre-sowing treatment of seed with different temperatures, in particular low temperatures. For example, in spinach (*Spinacia oleracea*), the times to 50% germination and final percentage germination were significantly improved by priming seed in PEG for 4 d at 10°C (Huang *et al*., 2002). Seed of "enset" (*Ensete ventricosum*) reached maximum germination after presoaking in an excess of water at 40°C for 24–48 h (Tesfaye, 1992). In tobacco, seed priming in PEG at different temperatures (15, 20 and 25°C) and different time periods (0, 1, 2, 3, 5, 10, and 15 d) determined that the

optimal condition was PEG priming at 25°C for 8 d (Min and Seo, 1999). Evaluation of different hydropriming temperatures (5–35°C) on seed germination of four range grass species, including bluebunch wheatgrass (*Pseudoroegneria spicata* [*Elymus spicatus*]), thickspike wheatgrass (*Elymus lanceolatus*), sandberg bluegrass (*Poa sandbergii*), and bottlebrush squirreltail (*Sitanion hystrix* [*Elymus elymoides*]), indicated that the most rapid germination was obtained at priming temperatures that were optimal for germination of untreated seeds (Hardegree, 1996). Therefore, the most effective priming temperature may vary with species.

Pre-sowing temperature treatment of seed can also alleviate the adverse effects of abiotic stresses on germination and emergence. For example, chilling treatment of *Brassica juncea* seed for 5, 10, or 15 d resulted in enhanced germination under salt stress (Sharma and Kumar, 1999). Similarly, chilling treatment of pearl millet seed for 2 d at 5°C increased the final germination percentage but not the germination rate under saline conditions (Ashraf *et al.*, 2003a). Similar alleviation of adverse effects of salt stress by pre-chilling has also been observed in other plant species, including Indiangrass (*Sorghastrum nutans*) (Watkinson and Pill, 1998) and parsnip (*Pastinaca sativa*) (Finch-Savage and Cox, 1982).

Although pre-sowing low-temperature treatment has been a more common and may be a more effective approach to improving seed germination under different environmental conditions, high-temperature treatment also has been practiced in some plant species. For example, in tomato, dry seed exposed to 50, 55, or 60°C temperatures for 15, 30, or 60 min showed increased germination rate when compared to soaked seed exposed to the same temperatures (Khalil and Moursy, 1983). Furthermore, in some species adapted to warm climatic conditions, seed priming with high temperatures has had positive effects on germination. For example, bitter gourd normally requires high temperatures (25–28°C) for successful seedling emergence, and poor emergence is common at sub-optimal temperatures. However, soaking seed at 50°C for 60 min and air drying to the original moisture level significantly improved seedling emergence at 25 or 20°C (Wang *et al.*, 2003). In contrast, in cotton, thermopriming seed at 40, 50, 60, or 70°C did not significantly change germination percentage, compared to untreated seed, and treatment at 80°C resulted in losing seed germinability (Basra *et al.*, 2004). Thus, different plant species may respond differently to pre-sowing treatment with high temperatures.

B. Effect of Thermopriming on Activities of Enzymes in the Germinating Seed

Rather limited information is available regarding the effect of thermopriming on the activity of enzymes taking part in hydrolysis of storage products during seed germination. In lettuce, seed primed at 15°C in aerated

solution of PEG and subsequently redried exhibited enhanced activity of endo-beta-mannanase during early hours of imbibition; the enhanced activity was greater in thermosensitive than thermotolerant genotypes (Nascimento *et al*., 2001). The authors suggested that priming overcame the inhibitory effects of high temperature in thermosensitive lettuce seed by increasing endo-beta-mannanase activity, which led to a weakening of endosperm and overcoming thermodormancy. In bitter gourd, thermopriming of seed improved low-temperature (20 °C) germination ability and seedling emergence in association with simultaneous increases in activities of enzymes such as isocitrate lyase, malate synthase, and malate dehydrogenase (Lin and Sung, 2001). In the same species, Wang *et al*. (2003) showed enhanced activity of certain antioxidative enzymes in germinating seed due to soaking in hot water (50 °C).

C. Effect of Thermopriming on Organic and Inorganic Substances in the Germinating Seed

Chemical changes that take place in the seed in response to thermopriming and which subsequently facilitate germination are not fully understood. Most seeds, including those that normally require pre-chilling treatment, contain lipids and proteins as their major storage compounds and very little amounts of starch. During chilling treatment, for example, the embryo may grow considerably, caused by mobilization of carbon and nitrogen compounds from storage tissues. Also, because of the breakdown of lipids and proteins, sugars accumulate to a great extent, and may be used as a source of energy and for generating osmotic pressure to facilitate water uptake and seed germination (Salisbury and Ross, 1992). Accumulation of sugars is a common phenomenon even in cold-requiring seed. It is also likely that, during cold treatment, if inhibitors are present in the seed, they are disintegrated, and plant growth regulators such as gibberellins and cytokinins are accumulated (Khan, 1977). In bitter gourd, changes in anti-oxidative activity in germinating seed due to warm-water (50 °C) soaking for 60 min resulted in marked increases in activity of anti-oxidative enzymes and levels of antioxidants during germination (Wang *et al*., 2003). A positive association between the anti-oxidative capacity retained in the treated seed and their germination ability was observed.

D. Effect of Thermopriming on Later Plant Growth and Metabolism

Treatment of seed with high or low temperatures may also promote later plant growth and final crop yield. For example, vegetative growth and final yield of spinach was markedly increased when plants were raised from seed treated with low temperature (10 °C) in PEG solution for 4 d (Huang *et al*.,

2002). Seed priming with high temperatures also may have similar effects. Tomato seed primed at 50 or 60°C resulted in significant increases in stem length, shoot weight, leaf area, number of flowers, fruit set, and final yield, with optimal results gained by priming at 60°C for 2 h (Khalil and Moursy, 1983). Also in tomato, seed soaked in water at 50, 60, or 70°C for 15, 5, or 1–2 min, respectively, produced plants that within 30 d after sowing were on average 20% taller than control plants (Klein and Hebbe, 1994). Similar beneficial effects of thermopriming were also observed in cotton (Shah *et al*., 2001). These reports suggest that treatment of seed with low or high temperatures has a promotive effect on later plant growth and final yield of different plant species, but the range of these temperatures for maximum effect may be different in different plants. Also, the time of seed exposure to these temperatures varies among species.

VII. PRIMING WITH PLANT GROWTH HORMONES

Presoaking seed with optimal concentrations of plant growth hormones is shown to effectively improve germination as well as growth and yield performance of various crop species under both normal and stress conditions (Darra *et al*., 1973; Hurly *et al*., 1991; Lee *et al*., 1998). Growth hormones normally used for seed priming include auxins (IAA, IBA, NAA), gibberellins (GA), kinetin, abscisic acid, polyamines, ethylene, brasinolide, salicylic acid, and ascorbic acid. Some osmoprotectants such as glycine betaine have also been used along with growth hormones as co-priming agents (Campbell *et al*., 1999).

A. Effect of Plant Hormones on Seed Germination and Emergence

Numerous studies have demonstrated improvement in seed germination of different plant species under both normal and stress conditions in response to priming with plant growth hormones or other organic substances. In pearl millet (*Pennisetum typhoides*), for example, seed treated with 100 mg/liter chlormequat chloride (CCC) or 0.15% succinic acid exhibited a higher percentage of germination than untreated seed (Shanmugasundaram and Kannaiyan, 1989). Similarly, higher percentages of germination were observed in sorghum, groundnut, pigeonpea, and cowpea seeds treated with succinic acid or CCC (Rangaswamy *et al*., 1993). In cotton, soaking delinted seed in 50 or 100 mg/liter GA for 16–24 h increased germination rate and percentage, where the effect was most pronounced with 100 mg/liter GA

treatment for 16 h (Varma *et al*., 1984). In the leguminous crop blackgram (*Vigna mungo*), 40 mg/liter GA was the most effective pre-sowing treatment for attaining maximum germination under non-stress conditions (Sharma and Saran, 1992). In sunflower, ascorbic acid was found to be very effective in promoting seed germination under non-stress conditions (Singh and Rao, 1993).

Seed treatment with growth hormones has also been shown to alleviate the adverse effects of salt stress during germination. For example, pre-treatment of sudangrass (*Sorghum sudanense*) seed with CCC or other priming agents counteracted the adverse effect of salt stress on rate and percentage of germination (Ismaeil *et al*., 1993). In wheat, while seed germination decreased with increasing levels of salinity, the adverse effect of salinity was alleviated by soaking seed with IAA, NAA, or GA (Balki and Padole, 1982). Similarly, wheat seed pretreated with different concentrations of GA showed varying positive results in terms of germination under saline conditions, with pre-soaking in 50 mg/liter of GA having the best result (Parashar and Varma, 1988). In a different study with wheat, adverse effects of salinity stress on seed germination were mitigated by soaking seed in varying concentrations of IAA, IBA, or gibberellic acid (GA_3) (Gulnaz *et al*., 1999a). For example, 200 mg/liter GA_3 resulted in 100% seed germination at 13.1 dS m^{-1}, while IAA and IBA increased germination at 8.4 dS m^{-1}. Similarly, pre-sowing seed treatment with GA was found to be very effective in alleviating the effects of salt stress in tomato (Kang *et al*., 1996) and okra (*Abelmoschus esculentus*) (Vijayaraghavan, 1999). In pigeonpea seed, pre-treatment with kinetin and ascorbic acid was very effective in mitigating the adverse effects of salt stress on germination (Jyotsna and Srivastava, 1998).

B. Effect of Plant Hormones on Enzyme Activities in the Germinating Seed

Only a few reports are available regarding the effect of hormones on activity of hydrolytic enzymes in germinating seed. In one study, triticale (×*Triticosecale*) seedlings raised from seed primed with varying concentrations of pyridoxine hydrochloride showed higher nitrate reductase activity under non-stress conditions (Ahmad *et al*., 1995). In another study, it was determined that wheat seed pretreated with 50 mg/liter of sodium benzoate or ascorbic acid showed higher amylase activity during germination under saline conditions than untreated seed (Roy and Srivastava, 1999). However, such limited studies do not allow drawing any conclusion as to the relationship between priming seed with growth substances and the extent of enzyme activities during germination.

C. Effect of Plant Hormones on Organic and Inorganic Substances in the Germinating Seed

Limited research has been conducted to examine the effects of pretreating seed with growth substances on organic metabolites or inorganic nutrients in germinating seed. In one study, treating pearl millet seed with GA_3 resulted in seedlings with higher levels of soluble proteins and free amino acids compared to seedlings of untreated seed (Gupta and Mukherjee, 1982). In this experiment, GA_3 treatment caused a retention of free N in the coleoptile and root rather than translocation of it to the primary leaf. Of different organic acids, succinic and malic acids were dominant, followed by citric acid, in all seedlings. Furthermore, the distribution pattern of organic acids in seedlings from GA_3-treated seed was closely associated with their rapid utilization in the synthesis of various amino acids and amides. Phosphoenolpyruvic acid and pyruvic acid were present in high concentrations in various seedling parts, followed by oxaloacetic acid. In another study, triticale seedlings raised from seed soaked in 0.001, 0.01, or 0.1% aqueous solution of pyridoxine hydrochloride showed higher accumulation of pyridoxine, chlorophyll, N, P, K, soluble and insoluble carbohydrates, and proteins, compared to untreated seed (Ahmad *et al*., 1995). However, whether such relationships would also be present in other plant species is yet unknown.

D. Effect of Plant Hormones on Later Plant Growth and Metabolism

A review of literature indicates that in many crop species, priming seed with growth substances not only enhances germination and emergence but also improves plant growth and final yield under non-stress and salt-stress conditions. For example, treatment of sorghum seed with 50 mg/liter of NAA, IBA, or GA, 25 mg/liter of IAA, or 4 mg/liter of 2,4-D increased the grain yield by 10% under non-stress conditions (Thakre and Ghate, 1984). Treatment of rice seed with uniconazole and paclobutrazol resulted in healthier plants with a higher dry-weight/plant-height ratio than untreated control plants (Choi *et al*., 1988). Triticale seedlings grown from seed soaked in 0.001, 0.01, or 0.1% aqueous solution of pyridoxine hydrochloride had increased shoot length, leaf area, fresh weight, and dry weight at 10, 15, 20, 25, and 30 d stages of growth compared to plants grown from water-soaked seed (Ahmad *et al*., 1995). An examination of faba beans and cotton (*Gossypium barbadense*) seed primed with different concentrations (20–60 mg/liter) of IAA determined that the most effective concentration of IAA for maximum yield for faba bean was 40 mg/liter, whereas for cotton it was

60 mg/liter (Harb, 1992). Furthermore, improvement in plant growth or final yield in response to seed priming with growth regulators has been reported in other plant species, including blackgram primed with GA_3, kinetin, NAA, Ethrel (ethephon), or IBA (Patel and Saxena, 1994), greengram (*Vigna radiata*) primed with CCC, cinnamic acid, or succinic acid (Sabir-Ahamed, 1999), and wheat primed with IAA, NAA, ascorbic acid, or succinic acid (Padole, 1981).

In some plant species, seed priming with growth substances has also been shown to alleviate adverse effects of salinity stress on growth and final yield. For example, soaking wheat kernels with GA_3 improved plant height, root length, and fresh and dry weight of stem, root and leaves under saline conditions (Parashar and Varma, 1988). Grain yield of pearl millet was improved under saline conditions by treating seed with 50 mg/liter GA and plant growth of bhendi (*Abelmoschus esculentus*) was improved under sodic soil conditions by treating seed with GA (Vijayaraghavan, 1999). There are also evidence of growth or yield improvement under saline conditions by using other plant growth hormones as priming agents, such as CCC in sudangrass (Ismaeil *et al*., 1993), 2,4-D (Gulnaz *et al*., 1999b), IAA, NAA, GA, ascorbic acid, thiamin and sodium salicylate in wheat (Al-Hakimi and Hamada, 2001; Balki and Padole, 1982), ascorbic acid, thiamin and pyridoxine in sunflower and maize (Ahmed-Hamad and Monsaly, 1998) and 28-homobrassinolide in mungbean (Fariduddin *et al*., 2003).

Seed priming with growth hormones brings about some biochemical changes in many plants grown under normal or saline conditions. For example, triticale plants grown under normal growth conditions from seed soaked in 0.001, 0.01, or 0.1% aqueous solution of pyridoxine hydrochloride showed increased accumulation of pyridoxine, chlorophyll, soluble and insoluble carbohydrates, N, P, K, and proteins, as well as high nitrate reductase activity (Ahmad *et al*., 1995). In both faba beans and cotton, seed treatment with GA at 100 mg/liter resulted in high contents of sugar, N, P, K, Ca, Fe, Zn, and Mn content in the shoot (Harb, 1992). Wheat plants grown under saline conditions from seed soaked in IAA, NAA, and GA showed increased growth and uptake of N, P, K, Ca, Mg, and B compared to control plants (Balki and Padole, 1982). In soybean, plants developed from seed treated with various concentrations of GA_3 and grown in salinized soil exhibited more vigorous growth compared to plants from untreated seed, although the treated and control plants showed similar uptakes of N, P, and K (Mahmoud and Abdel-Aziz, 1985). In wheat, soaking seed in ascorbic acid, thiamin, or sodium salicylate before germination counteracted adverse effects of NaCl on adult plant growth, most likely by suppression of salt stress-induced accumulation of proline (Al-Hakimi and Hamada, 2001). Priming of sunflower and maize seeds for 6 h in 50 mg/liter solution of ascorbic acid, thiamin, or pyridoxine promoted plant

growth and photosynthesis and alleviated, at least partially, the adverse effects of salinity; the latter was most likely due to increasing the efficiency of water uptake and protecting the photosynthetic pigments and apparatus (Ahmed-Hamad and Monsaly, 1998). In a similar study, an increase in photosynthetic capacity under normal growth conditions was also observed in mungbean plants raised from seed treated with 28-homobrassinolide solutions (Fariduddin *et al*., 2003).

From the above-mentioned reports, the potential benefits of different growth substances as seed-priming agents are evident. However, some of the growth substances are very expensive, and their use by farmers may not be economically beneficial unless the cost-benefit ratio can be reduced. In the short run, there is a need to identify growth substances that are relatively cheap and easily available, yet effective.

VIII. BIOPRIMING

In most plant species, seed and seedlings are prone to decay caused by seed-borne or soil-borne diseases. Such decay often results in reduced germination and seedling emergence and poor crop establishment and low yield. In most cases, chemical control is a routine preventive measure. However, biopriming, which is coating seed with a bacterial biocontrol agent followed by incubating the seed under warm, moist conditions, is an effective alternative to chemical control. It is a priming procedure that integrates pre-sowing seed hydration with biological seed treatment. Following such a treatment, the seed may be planted or dried for storage. Biopriming using naturally occurring soil microorganisms is a safe, non-polluting, and environmentally sound disease control measure and an effective pre-sowing seed treatment. There are some known beneficial bacteria and fungi which, if applied to seed prior to planting, may enhance plant growth and development.

Biopriming allows rapid colonization of the beneficial organism(s) on the seed, and often results in a more uniform coverage of the seed surface compared to other priming techniques (Smith, 1996; Warren and Bennett, 1997). Some biological agents can also be added to the seed during priming with aerated, diluted salt solutions. For example, a good crop stand establishment was obtained in tomato using seed that were bio-osmoprimed in aerated −0.8 MPa solution of $NaNO_3$ at 20°C with nutrient broth and bacterium *Pseudomonas aureofaciens* (Warren and Bennett, 1997). In carrot, seed naturally infected with the pathogens *Alternaria radicina* and *A. dauci* were primed with water or bioprimed with the fungal antagonist *Clonostachys rosea* (Jensen *et al*., 2001). It was determined that regular water priming resulted in an increase in the incidence of *A. radicina* and *A. dauci* from

about 32–35% to 59% and 86%, respectively, whereas biopriming caused a 4% and 2% reduction in the incidence of the two natural pathogens, respectively. Furthermore, the bioprimed seed resulted in a complete eradication of *Alternaria* pathogens on the seed and a significantly higher stand establishment compared to seed primed with water.

Currently, biopriming is a common practice in the seed industry worldwide. During the seed coating process, inoculants, fungicides, or insecticides are added together with other substances, which provide a protective barrier on the seed. Biopriming has been shown to be more effective than regular chemical treatment for disease control. For example, in sweet corn, biopriming provided better protection against pre-emergence damping-off when seed were planted in cold or warm soil (Callan and Mathre, 2000; Mathre *et al*., 1994). The coating process commonly used in the forage seed industry often employs limestone coating and a bacterial inoculant (Ni, 1997). A systemic fungicide such as metalaxyl [*N*-(2,6-dimethylphenyl)-*N*-(methoxyacetyl) alanine methyl ester] is often added in the coating process, usually for control of *Pythium* and *Phytophthora* spp. Mineral nutrients are also included in some cases. Coating of alfalfa seed resulted in improved *Rhizobium* survival and early nodulation of seedlings (Horikawa and Ohtsuka, 1995a,b; Sheaffer *et al*., 1988). However, in these studies, coated alfalfa seed did not show a consistent advantage over uncoated seed in terms of stand establishment and forage yield. Other studies have produced mixed results as to the effects of seed coating on forage yield (Canestrino *et al*., 1998; Horikawa *et al*., 1996; Marble *et al*., 1990; Twidwell and Gallenberg, 1993). In general, the decision on whether to use a seed enhancement treatment should be based on soil type, field history of disease problems, and cost of the treatment (Twidwell and Gallenberg, 1993). However, further research is necessary to determine specific situations in which coating and pelleting may be of value in improving crop stand establishment and final yield. Furthermore, more research is needed to identify additional beneficial strains of bacteria and fungi for individual crop species and to develop efficient techniques for their application.

IX. DRUM PRIMING

In drum priming, seed are hydrated in a tumbling drum using a precise volume of water. The amount of water is limited so that it is less than the amount needed for natural imbibition and seed germination to occur. Drum priming enhances seed performance without the waste and additional materials associated with the conventional osmotic or matric priming techniques, and thus has advantages over these methods. Drum priming entails the following four separate phases:

Calibration: The desired amount of water to be added to the seed is determined.
Hydration: The appropriate time period during which the seed achieve the desired moisture level is determined.
Incubation: Seed are maintained at or near the moisture level to receive the desired hydration, typically up to 14 d.
Drying: The added water is removed so that seed are brought to their original water content.

Commercially, controlled hydration of seed to the desired level by drum priming is achieved by addition of a given amount of water over time (Rowse, 1996). The duration of the process depends on the absorptive characteristics of the species and the seed lot (Mauromicale and Cavallaro, 1995). In European models, the drum is placed on a sensitive scale that determines seed weight increase caused by a constant influx of water (Rowse, 1996). Once seed have achieved the desired moisture level, the hydration phase is terminated. Hydrated seed can then be incubated for the period of time required for effective priming before they are re-dried. Using different water levels and hydration periods, Warren and Bennett (1997) determined that drum priming could provide a better alternative to osmotic or matric priming for improving crop stand establishment in two genotypes of sweet corn. More recently, the applicability of drum priming for introducing microbial inoculants such as bacteria and fungi was assessed on seed of carrot, leek, and parsnip (Wright *et al*., 2003). Irrespective of the seed type, drum priming resulted in significant increases in populations of *Pseudomonas*, that is, up to 10% of the culturable bacterial population, which also decreased little by re-drying. In the same study, fungal populations also increased significantly during seed priming in the three vegetable crops and were little affected by re-drying. Furthermore, addition of a tefluthrin (a standard commercial insecticide) coating during the drying stage of the commercial drum priming had little effect on microbial populations. In view of these results, Wright *et al*. (2003) recommended drum priming as a novel method for introducing microbial inoculants onto the seed. However, the usefulness of this technique in other plant species needs to be established in the future.

X. OTHER PRE-SOWING SEED TREATMENTS

Seed of different crop species vary in size, shape, and color. In some cases, the seed size is so small that uniform sowing may not be possible. Also, the seed must be protected from various pests and diseases that might attack the germinating seed and seedlings. Seed coating technologies, however, have

recently gained significant advancements in alleviating various potential problems (Halmer, 1988, 1994; Taylor *et al.*, 1998). Some other common seed-coating practices are as discussed below.

A. Seed Pelleting

This is a special type of seed treatment in which many materials, including mineral nutrients, plant growth regulators, agricultural chemicals, water absorbents, and fillings are mixed and uniformly coated onto the surface of the seed. Pelleting makes the seed's shape round and regular, enlarges its size, and improves its mobility. This technique was developed in the 1940s with the primary purpose of converting individual or groups of small, irregularly-shaped seeds into spherical capsules that would ensure precision planting (Halmer, 1988; Ni, 1997). Since then, it has been developed into a highly sophisticated seed treatment technology to change the physical shape of a seed, enhancing its handling and plantability. This technique, however, requires specialized application machinery and expertise, and is a rather expensive practice (Scott *et al.*, 1997). Seed can be pelleted with different materials according to their quality, physiological characteristics, plant's diseases and insects, and soil's nutrients. The pellet must be robust enough to withstand handling, transportation, and attrition during sowing. Once sown, the pelleting layer must break up quickly so as not to suppress germination. Binders are typically used to improve the durability of the pellet. Materials used for pelleting provide the seed with nutrients and energy during germination and seedling growth and a good environment for root growth. Changing the composition of the filler or cementing materials can alter water-holding capacity of the pellet. The pelleted seed is not only used for precision seeding, but also may bring about a high-yield, high-quality crop.

In order to improve sowing efficiency, seed of many high-value crops are usually pelleted using inert filler materials, including chalk, peat, and sand, which are mixed with adhesives such as calcium sulfate and starch, using rotating mills. In some cases, the filler may also contain seed-treatment products. For example, rice seed is pelleted with calcium peroxide to increase oxygen availability in submerged paddy conditions (Halmer, 1988, 1994). Fungicides and microbiological inoculants can also be applied to pellets for protecting seed from soil-borne pathogens (Scott *et al.*, 1997).

B. Film Coating

This coating technique has been adopted from pharmaceutical and confectionery industries for uniform application of coating materials onto the seed. The film-forming products are usually comprised of a mixture of

polymers, plasticizers, colorants (dyes), and biological agents, which do not alter the physical properties of the seed (Halmer, 1994; Ni, 1997). This technique, however, requires sophisticated and specialized equipment to precisely spray the seed with relatively large quantities of formulations and polymer binders, and simultaneously dry the added materials so as to ensure maintenance of normal seed moisture content (Halmer, 1994). To apply different solutions sequentially, seed are passed through several cycles of spraying and drying. Film coating is a proven and standard method for applying fungicides, bacterial inoculants, and other chemicals to vegetable seed (Ester, 1994). In Europe, however, seed of field crops such as maize, oilseed rape, and sunflower are also treated with film-coating materials (Barlett, 1994; Taylor *et al.*, 1998). In the United States, film coating of the seed is becoming more popular. Various effective fluidized bed systems for film coating have been described (Bacon *et al.*, 1988; Horner, 1988). In sprouted bed systems, for example, seed are coated by a mist of chemical formulations as they move through an air stream in a systematic flow pattern. In drum coaters, seed are held in a rotating drum with installed spraying units. Dry, warmed-air is flown through perforations in the drum wall and holds the seed in a fluidized state. Stirrer blades gently mix the seed to ensure uniform coverage from spray nozzles (Halmer, 1994).

The major beneficial features of this technology include reduced dust-off of chemicals, uniform coverage on individual seeds, and improved flow through the planter. In demonstrating the potential use of film coatings as moisture barriers for seed stored at high humidity, McGee *et al.* (1988) determined that a polyvinylidene chloride copolymer emulsion applied to maize and soybean seeds effectively controlled storage fungi attack during storage for up to three months at 85% relative humidity and 25°C. In contrast, Arias-Rivas (1994) discovered that polymer film coatings applied alone to seed could not provide protection against *Pythium* spp. infection of maize seedlings under field conditions. However, despite the potential benefits of film coating, some harmful effects have also been noted. For example, like pelleting, film coating may act as a physical barrier to leaching of inhibitors from the seed and limit oxygen diffusion to the growing embryo (Duan and Burris, 1997).

C. Fluid Drilling

In this method of priming, seed are mixed in a liquid gel and subsequently planted in the field. Both chemical and biological control agents can be applied by this technique. For example, metalaxyl, etridiazole, and captan applied by fluid drilling controlled *Pythium* damping-off of tomatoes (Taylor and Harman, 1990). In the same study, proliferation of *Enterobacter* spp.

was found in priming solutions, which provided protection for sugarbeet seed planted in *Pythium*-infested soil.

XI. CONCLUSIONS AND FUTURE PROSPECTS

In many crop species, biotic and abiotic stresses, including diseases and insects, extreme temperatures, soil crusting, excess or limitation of water, and salinity, may individually or in combination adversely affect the germination process, leading to reductions in the rate and final percentage of germination, poor stand establishment, and low crop yield. However, if the stress effect can be alleviated at the germination stage, chances for attaining a good crop with economic yield production would be higher. Some chemical or physical treatments of seed prior to sowing can in fact significantly alleviate adverse effects of the germinating environment. For the past two decades, seed priming, that is, pre-sowing controlled imbibition of seed followed by dehydration, has become a common practice to increase the speed and uniformity of germination and emergence under both non-stress and stress conditions. In practice, the main purpose of priming is to partially hydrate the seed to a point where early phases of germination processes begin, but radicle emergence is prevented, before sowing the seed. Various seed-priming techniques have been developed and effectively used in different crop species.

Different methods have advantages and disadvantages and may not all be equally effective or profitable to use in different crops. Also, the effect of each priming technique may vary from species to species and in different stages of plant development. In general, chemical treatments have been used more often and more effectively than biological treatments, as their formulations and treatment standards are well developed. However, some biological treatments have also been effectively used in combination with chemical or physical priming treatments to further enhance germination and seedling emergence under non-stress and stress conditions. To determine the effectiveness of different priming techniques, factors such as concentration/dose of priming agent, time period for incubation of seed in priming agent, and seed storability must be examined and the optimal conditions determined.

To improve the utility and cost efficiency of different seed priming techniques, it is necessary to understand the metabolic events that take place in seed during priming and subsequent germination. It is already known that priming contributes to metabolic repairing in the seed during initial imbibition, building-up of the germination-enhancing metabolites, osmotic adjustment, and the reduction in the lag time of imbibition. However,

knowledge of the ultrastructural changes or activation of metabolic processes that incept during priming or germination of primed seed is scarce. In most endospermic seed, the endosperm surrounding the embryo presents a physical barrier to radicle emergence. Hydrolysis of endospermic tissue is a prerequisite for the emergence of embryo during germination. In some species, images taken with a scanning electron microscope have provided evidence of enzymatic degradation of endosperm during seed germination. It has also been shown by the Instron Universal Testing Machine that the strength of endospermic tissue reduces during germination. Furthermore, it is known that endomannanase, galactosidase, and mannohydrolase are the major enzymes responsible for the breakdown of endodermis. However, the extent to which these enzymes are activated by seed priming is not fully known. Characterization of the expression of these hydrolyzing enzymes in different plant species during seed priming and determination of the potential relationships between their expressions and germination improvement in primed seed can help improve utilization of different priming techniques. Furthermore, regulation of cell cycle events has emerged as a promising process in characterizing the effect of priming on seed germination. As division and differentiation of cells take place, microtubules undergo rearrangement to new configurations that are dependent on the interactions with microtubule-associated proteins such as ß-tubulin polypeptides. Detailed studies are required to determine the extent to which these tubulin proteins accumulate in seed of different plant species with different priming techniques.

Laboratory experiments on seed priming require scaling-up of procedures to treat large quantities of seed for use under field conditions. These scaling methods could be useful in determining the optimal priming conditions regarding temperature, water, and time of treatment prior to bulk priming. Furthermore, the amalgamation of seed research with new advancements in molecular biology is central to the understanding and integration of multiple mechanisms that can lead to enhanced seed germination, improved stand establishment, and higher crop yield due to different methods of seed priming.

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Methodologies and the Practical Aspects of the Bulk Soil EC (σ_a)—Soil Solution EC (σ_w) Relations

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The total concentration of ions present in a solution is a useful indicator for salinity in fields like hydrology, environment, industry, and agriculture. Salinity evaluation in agricultural activity may be connected to research and application processes: osmotic pressure, leaching, water bodies mixing, irrigation management, water pricing, and water allocation. An immediate and simple means for salinity level evaluation is the measurement of the soil (or any other porous media) electrical conductivity (σ_a). Until the TDR-era, σ_a and soil volumetric water content (θ) were measured by two separate techniques and inevitably not in the very same spot. The introduction of TDR into soil science enabled the measurement of these two soil properties in exactly the same volume, with the highest accuracy. Moreover, pre-TDR calculation models could be readopted and applied to handle the newly obtained data. This review voluntarily confines itself to the practical aspects of accurately converting σ_a into σ_w for different soil types, moisture levels, and solution chemical compositions. Subsequently, a short background description of pre-TDR measurement methods and calculation techniques and the basics of TDR methodology are presented, and three procedures for σ_a calculations are discussed, of which the Giese-Tiemann stands out as the most recommended. Special attention is given to the once popular Dalton *et al.* (1984) model. Following are nine presented and compared protocols

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suggesting ways to evaluate σ_w from σ_a, θ, and soil properties. Light is thrown on the extent and significance of the curvilinearity of the $\sigma_a - \sigma_w$ relations for $\sigma_w < 4$ dS m^{-1}. The conclusions sum up those field situations deserving special care along with ideas about further research needed to increase acceptance of the TDR technology for monitoring salinity by farmers. As always, we should remember with respect the contribution of the previous generations (Cremers, Sauer, Spiegler, Laudelout), whose deep theoretical understanding and originality were their main tools for laying the foundations for the better-equipped generation that followed to put their ideas into practice.

ABBREVIATIONS

θ (L L^{-1})	volumetric water content
σ (dS m^{-1})	electrical conductivity
(e.g. σa	of the bulk soil
σ_w	of the soil solution
σ_s	of the solid phase surface
σ_e	of an aqueous saturated extract corrected for the dilution
$\sigma_{w,ext}$	during the extracting stage relative to natural θ
ε	dielectric constant
F	formation factor
TDR	Time Domain Reflectometry
Z_L (Ω)	impedance load
σ–ε dual method	TDR-based instruments like the Tek1502 or any others that are capable of measuring simultaneously both the resistivity and capacitance

I. BACKGROUND

The measurement of electrical conductivity (EC, σ) is an attractive method by which to measure total ion concentration since it is easy, simple, inexpensive, and relates well to it (Moore, 1962: U. S. Salinity Laboratory Staff, 1954). σ metering methods are widely used in basic scientific, agricultural, and environmental studies: for example, water and solute transfer, salinity level evaluation in laboratory and greenhouse experiments, management practices such as irrigation scheduling, drainage, and salt load monitoring, pollutant movement, or hazardous leaking from disposal sites.

Unlike solutions, in solid-liquid media (e.g., soils, artificial root beds, mine wastes, aquifers) the conversion of measured bulk σ (σ_a) to *in situ* $\sigma_{interstitial\ water}$ depends, among other system factors, on the water content (WC, θ). Until about 20 years ago, θ was obtained by resistance blocks, tensiometers, heat dissipation sensors, neutron moderation meters, or gamma attenuation, all calibrated against gravimetric determination of the water content. Alongside, σ_a was obtained from resistivity measurements by the Wenner array (Wenner, 1916) and later the four electrode method (Rhoades and van Schilfgaarde, 1976). σ_a and θ were measured separately, commonly in adjacent locations, and spatial uniformity was assumed for σ_w calculation. The introduction into agricultural sciences of the Time Domain Reflectometry (TDR) technology (Topp *et al.*, 1980), which measures θ and σ_a simultaneously and in the same soil volume, revolutionized σ_w evaluation until it became the reference method in spite of its high costs.

To keep this review focused, aspects clearly presented in previous reviews will not be repeated. From two or more articles expressing similar ideas, only one was selected. This review aims at those interested in accurate evaluation of the total concentration of a solution found in the pores of porous media. The review is limited to discussing ways to convert bulk EC (σ_a) data into interstitial solution EC (σ_w) after the needed parameters were properly obtained. For a wider background, the reader is directed to Topp *et al.* 1980 (pioneering article on soil θ measurement); Zegelin *et al.* (1989), and Cassel *et al.* (1994), discussing basic TDR operation and its properties, construction of TDR systems, θ calculations; Noborio *et al.* (1994) and Noborio (2001), who expand on the relevance of TDR probes length, rods number, spacing and diameter, installation, and spatial variability on the measurement of $\sigma_{soil\ pore\ water}$; Robinson *et al.* (2003) in the latest review on the advances in the TDR technique; and Friedman's (2004) most recent, methodical review on the soil properties that influence σ_a and their use in the different approaches and calculation models.

II. BEYOND THE SCOPE OF THE REVIEW

1. **An upper limit** of $\sigma_a \leq 3.5$ was arbitrarily chosen for this review, to include most crops of significant yields and economic value, but to omit higher salinity values that induce acute yield reduction. These should be studied from industrial or environmental aspects.

2. Soil volume size and measurement accuracy. This review is focusing on studies aiming at small scale (0.1 to a few liters), accurate σ_w evaluation, which distinguish between the separate contributions of the porous system

components and their mutual interactions. Except for the TDR, three kinds of portable resistivity sensors are available: (i) under-surface-installed four-electrode sensors (Rhoades and van Schilfgaarde, 1976), (ii) surface-array resistance sensors (Wenner array), and (iii) EM induction sensors (Geonics EM38). The four-electrode sensor is directly inserted by preaugering to the depth of interest. An accurate, direct-contact σ_a value is obtained, representing a soil volume of ~ 0.1 L. The other two sensors are depth-weighted σ_a, and the weighting functions vary with the configuration of the electrodes, or electromagnetic coils, frequency of electrical current used in the measurement, distribution of σ_a within the various depths of the soil profile, and other factors. They provide empirical, broadly correlated, and widely scattered data. These sensors, plus some site-specific calibrations, are usually adopted as survey tools for salinity assessment, precision agriculture (Corwin and Lesch, 2003), and mapping (Lesch *et al.*, 1992).

Examples: Linear correlation coefficients ranging from 0.61 to 0.98 were found between $\sigma_{soil\ paste}$ and Wenner array σ (Read and Cameron, 1979) with a standard deviation of up to 4 for a σ_a =7 dS m^{-1}. The EM38 instrument (Rhoades and Corwin, 1980) has been used to survey large areas to indicate the extent of salinity by measuring σ_a of the soil profile. The device sensitivity varies with depth, orientation, height from the soil surface, salinity-water content, degree of homogeneity, and the interaction among all of the above-mentioned parameters such that the error in average σ_a value compared with that of the resistivity four electrode probe is slightly higher (~15% according to Rhoades and Corwin [1980]), or significantly higher according to Slavich and Petterson (1990). For a depth of 0–0.6 m in a high clay soil with high salinity the calibration becomes non-linear. Sudduth *et al.* (2001), applying the EM38 for precision agricultural practices, found difficulties in separating the dependency of measured σ_a on σ_w, θ, topsoil depth, clay content, clay mineralogy, soil pore size distribution, temperature, season, and, to a smaller extent, the variation in sensor operating speed and height and drift over time. The reason is inherent to the system. On one hand, assuming all other conditions are constant, a high clay content soil is closely associated with higher levels of θ, σ_s, and salt accumulation (due to slower leaching rates). However, on the other hand, the contribution of these three parameters to σ_a cannot be separated. Moreover, their effect on σ_a will be contradicting, thus resulting in less accurate σ_w (see also Sudduth *et al.*, 2003, and Heiniger *et al.*, 2003). Only site-specific calibrations, often with each measurement set, enabled use of within-field σ_a data for evaluating depth of topsoil, profile WC, clay content, and soil drainage class, with accuracies up to ±70% — below the limits set for this review.

3. Relations between the aqueous extracts and resistivity-obtained σ_a, converted to σ_{ext}. σ of saturated aqueous soil sample extracts (σ_{ext}) is probably the most common salinity appraisal technique, yet caution should

be practiced when comparing results of these two methods. θ_{soil} changes may modify the σ_w of the soil solution by varying the amount and composition of the dissolved ions. Unless the soil is very sandy and the majority of the ions originate from soluble salts, only a limited correlation between σ_{ext} and σ_w is expected. Nadler (1997) reports the differences between dilution-corrected aqueous soil extracts ($\sigma_{w,\ ext}$) and σ_w relations for three soil types. For the sand, the relations were almost linear and well correlated (R = 0.92). $\sigma_{w,\ ext}$ data points were 0.5 – 2.0 dS m^{-1} above the 1:1 line as a result of disturbing the θ-dependent chemical equilibrium by the extraction process and carrying it over, by adjusting calculations, to lower levels. For the loam, the relations were still linear but there was higher scatter (R = 0.76) and $\sigma_{w,\ ext}$ data were evenly spaced above and below the 1:1 line. For the clay, totally different relations were found, composed of two seemingly non-related parts. In one part, for a θ increase from 0.1 to 0.4, $\sigma_w = 1.3 \pm 0.3$ dS m^{-1} and the $\sigma_{w,\ ext}$ ranged from 4 to 20 dS m^{-1}. In the second part, the σ_w increase was from 2 to 6 and $\sigma_{w,\ ext}$ values fluctuated between 2.5 and 4.5 dS m^{-1}. With an increase in θ, σ_w decreased in a small (sand) or larger (loam) amount of scatter, while for the clay soil the decrease started at $\theta > 0.6$ only. The expectation for a constant product $\sigma_{w,\ ext} * \theta$ at high θ values contains an assumption that the solute chemical composition and the dilution effect on ionic activity coefficients (the ionic property used for estimating concentration from σ measurements) are constant. However, the dilution by addition of water in the high θ levels of the sand and the clay caused a relative increase in concentration for divalent (over monovalent) ions in solutions, so that the same total salts (equivalents) content was represented by a somewhat lower $\sigma_{w,\ ext} * \theta$ value. This indicated that a simple correction for the dilution (extracting) effect is not enough to reconstruct the real salinity, particularly for higher clay contents and in the presence of slightly soluble minerals.

In a field experiment where three salinity levels of irrigation waters (0.8, 1.3, and 1.7 dS m^{-1}) were used, measured salinity levels depended on the monitoring technique. Aqueous extracts ($\sigma_{w,\ ext}$) vs. the $\sigma_{four\text{-}electrode}$ consistently differed by 50% for a sandy soil (Nadler and Erner, 1998). The advantage of the resistivity results was supported by (i) a closer agreement to salt input mass balance, (ii) having more systematic salinity seasonal changes, and (iii) a more reasonable level of calculated leaching fractions.

4. $\sigma_{w\ effect}$ on θ (in the adopted limit of σ_a <3.5). A few articles (White *et al.*, 1994, and references therein, Sun *et al.*, 1999) claim that θ_{TDR} is σ_w dependent, which complicates the conversion of σ_a into σ_w. Such conclusions may be reached from preliminary experiments, using software based on TDR trace evaluation, by not adjusting the observed endpoint of layered media, and by incorrect data interpretation that will rarely be encountered

under routine agricultural production conditions. Only recently Nichols *et al.* (2002) reported that, although high σ_a levels (up to 5 dS m^{-1}) reduce the quality of TDR waveforms by the loss of signal amplitude, standard three-rods TDR wave-guides can accurately determine the signal travel time in saline solutions. Experiments in saturated and unsaturated soils, apparently showing that increasing the concentration of dissolved ions in soil water increased the measured travel time (e.g., by Wyseure *et al.,* 1997), were questioned by Nadler (1999). Sun *et al.* (1999) conducted a series of laboratory experiments in which they concluded that at the same θ, the travel time in a saline soil was longer than that in a non-saline soil, which leads to an overestimation of θ. This artifact is clearly shown in Fig. 6 of Sun *et al.* (1999). The difference found in travel time is caused by a later time point selected for the saline solution when applying the dual-tangent approach. In this technique, the reflection point is selected where the line with the deepest slope intercepts the extrapolated baseline. In the author's opinion, this is not a good approach. Originally, in order to avoid mistakenly choosing noise-caused, random peaks, the above interception technique was adopted. It is useful and safe as long as no parameter, except θ, affects the slope of the reflected signal, which is usually the case under low or medium total σ. However, when the medium's σ is high (regardless of its source: exchangeable ions, higher θ, or more concentrated pore solution), the slope of the reflected pulse is significantly decreased, significantly shifting the "end point." This is not due to a real increase in travel time but rather to an improper use of a tool to determine this value. S. Green (Hortresearch, Palmerston North, NZ, personal communication) used the dual-tangent approach in his software for identifying the reflection point in commonly well-leached, low salinity soils of New Zealand. He was convinced that the algorithm in his software should be changed when applying it to soils that were artificially salinized in laboratory experiments. The solution, adopted by the present author during the last 15 years, is to select both the beginning (pulse entry to the rods) and the end (reflection point) points of signal travel where the first, significant deviation of the trace from the baseline occurs. The reader's attention is drawn to a compilation of over 20 studies of soils with a wide range of clay, organic matter, and salt contents, (Nadler *et al.*, 1999) in which non-, over-, and under-estimations of θ due to salinity are reported. (From this point on θ will not be discussed.)

5. Exceptional cases. A few cases with exceptional results are reported by Nadler (1997). Vogeler *et al.* (1996) reported an experimental linear relation reached by a systematic, gradual shift in soil moisture and concentrations. However, they overlooked that during their calibration the differential wetting volume inevitably changed the chemical composition of both the solute and the solid exchangeable cations. Another unusual case of the θ effect on

σ_a–σ_w comes from Bottraud and Rhoades (1985). They reported larger increases of 266, 336, 530, and 1330% in σ_a for θ changes of 0.019, 0.022, 0.027, and 0.034 dS m^{-1}, respectively when the solids were wetted with 0.02 and 0.1 M $CaCl_2$ solutions.

A. The TDR Methodology

An electromagnetic (EM) pulse composed of a wide range of frequencies (10 kHz to 1.4 GHz) is formed in the transmitter. Most commonly used is the Tektronix 1502 cable tester (Beaverton, Oregon), which in a very short time (200 psec) is launched, through a coaxial cable, into a wave guide (= the TDR probe). The propagation velocity of the EM pulse generated by the TDR is $Vp = L/t$, where L is the distance (m) and t is the time (sec). Vp is also related to the dielectric constant (ε) through $Vp = c/\varepsilon^{0.5}$, where c is the speed of light. Using $\varepsilon = (ct/2L)^2$ and rearranging results in $\varepsilon = (la/L)^2$, where la is the measured (apparent) distance from the beginning to the end of the wave guide and L is the real (physical) length. A widely used equation relating ε to θ was given by Topp *et al.* (1980):

$$\theta = 5.3\,10^{-2} + 2.92\,10^{-2}\,\varepsilon - 5.5\,10^{-4}\,\varepsilon^2 + 4.3\,10^{-6}\,\varepsilon^3$$

where θ is the major soil parameter affecting $\sigma_a - \sigma_w$ relations. The voltage amplitudes of the reflected and transmitted EM pulse are measured as a function of time and presented by a sampling scope (Fig. 1).

Any change in impedance along the wave guide will result in a partial or total reflection of the EM pulse.

From the ratio of the above voltages the reflection coefficient is calculated by:

$$\rho = (V_r/V_0) = (Z_L - Z_0)/(Z_L + Z_0) \quad (1)$$

When the EM pulse travels through a waveguide embedded in the soil, the amplitude of the waves are attenuated due to dielectric losses and the electrical conductance of the soil. In waveguides of normal length, the duration of the transmission of the EM pulse from the cable tester is long compared with the travel time of the EM pulse in the waveguide. Thus, the TDR probe embedded in the soil can be viewed as a lumped circuit element with impedance Z_L at the end of a low-loss waveguide, with a characteristic impedance Z_0 (Lancaster, 1992; Nadler, 1991). Throughout the following discussion, TDR-based instruments like the Tek1502, or any others that are capable of measuring simultaneously the resistivity and capacitance of a medium, will be referred to as σ-ε dual method.

B. Calculating σ_a from Bulk Resistivity or TDR Traces

(1) The load impedance (R_L) can be calculated from ρ when measured after the voltage along the waveguide has reached a constant value, that is, after all multiple reflections have faded away. According to Fourier transform theory, low frequencies in the frequency domain correspond to long times in the time domain (Heimovaara *et al.*, 1995). At very low frequencies Z_L equals the load resistance (R_L of the TDR probe embedded in the soil), hence:

$$R_L = Z_0((1 + \rho_\infty)/(1 - \rho_\infty)) \quad (2)$$

where ρ_8 is ρ determined after all multiple reflections have faded out. The reciprocal of R_L equals the direct current conductance and can be converted to bulk soil EC ($_a$) by applying the geometric cell constant Kc of the TDR probe in

$$\sigma_a = Kc * f_T/R_L \quad (3)$$

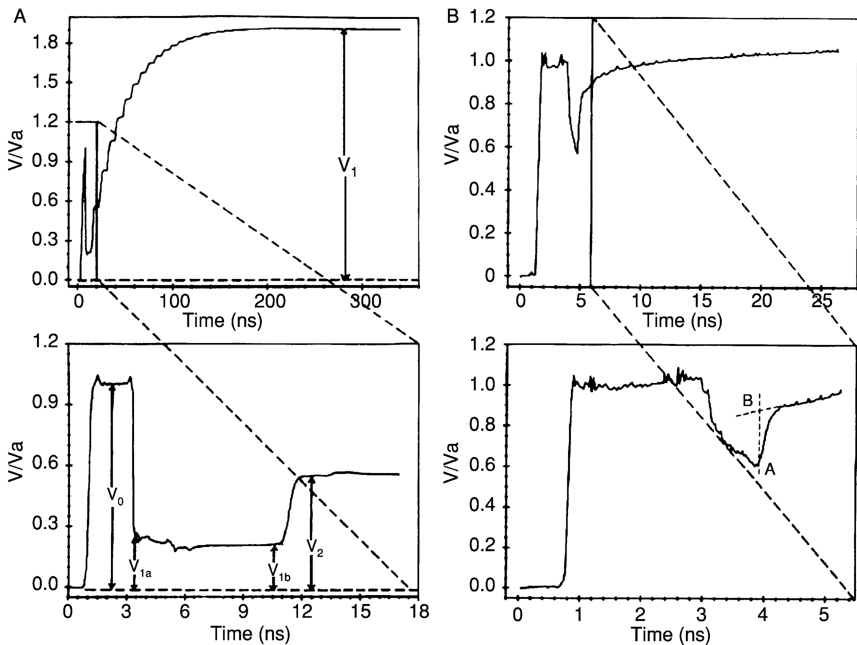


Figure 1 (A) An actual TDR trace from measurement on distilled water having numerous multiple reflections. The inset shows the expansion of the portion corresponding to signal traversing the sample once; (B) A TDR trace for soil showing that the multiple reflections from the sample boundaries are not detectable but the voltage rise is not easily defined without extrapolation to a given time as shown by A and B.

where f_T is the temperature factor. f_T of σ_a equals that of soil extracts, and the T correction of σ_a can be carried out as in pure liquids. Kc is determined from measurement of R_L in solutions of known σ_a.

The method, based on equations 1–3, is identical to the approach of Giese and Tiemann (1975), as shown by Heimovaara (1992), and will henceforth be called $\sigma_{a,\ G\text{-}T}$.

(2) A second method to evaluate σ_a, belonging to the disturbed circuit analysis type, was reported by Dalton *et al.* (1984). Basically, the relationships of signal amplitudes along the probe rods in a conducting medium can be described by:

$$(V_r - V_t) = V_t e^{(-2\alpha L)} \tag{4}$$

where V_t is the signal amplitude after partial reflection from the beginning of the probe, V_r is the signal amplitude after reflection from the end of the probe, and α is the attenuation coefficient expressed as $\alpha = 60(\pi\sigma/\varepsilon^{0.5})$ (Dalton *et al.*, 1984). Combining the last two equations results in:

$$\sigma_{a,D} = (\varepsilon^{0.5})/(120\Pi L)\ln(V_t/(V_r - V_t)) \tag{5}$$

(3) A third approach was reported by Topp *et al.* (1988), who compared an analysis of σ_a based on the signal attenuation after one "round-trip" with the Giese Tiemann (G-T) thin section approach, to the direct, experimental, low-frequency conductance bridge measurements in both solutions and soils. The good agreement between the above three analyses in solutions indicated the negligibility of the imaginary part of the complex dielectric constant. In soils, however, the analysis of signal after one-round-trip approach overestimated σ_a by up to 100%, and was most pronounced when σ_a <0.5 dS m^{-1}. This may be because ε'' is not negligible. Additionally, wider scope conclusions regarding the propagation of an EM pulse can be drawn from the difference in behavior between solutions and wet soils. Unlike solutions, wet porous media may filter the frequencies composing the TDR EM pulse, thus shaping to the TDR waveform. Practically, it implies that extra caution should be exercised in wet porous media when applying conclusions or calibrations obtained from pure solutions (Tyc *et al.*, 1988).

Nadler (1991) compared three different methods to calculate σ_a (Dalton *et al.*, 1984; Topp *et al.* 1988; Zegelin *et al.*, 1989) to the Giese-Tiemann ($\sigma_{a,\ G\text{-}T}$) method, with experimentally (four-electrode probe) measured σ_a. Only the $\sigma_{a,G\text{-}T}$ was in good agreement with the experimental results. The other three approaches all tended to overestimate σ_a, indicating that the contribution of dielectric losses to σ_a inherent in the disturbed circuit analysis cannot be neglected (Nissen *et al.*, 1998; Zegelin *et al.*, 1989). Using Dalton's calculation,

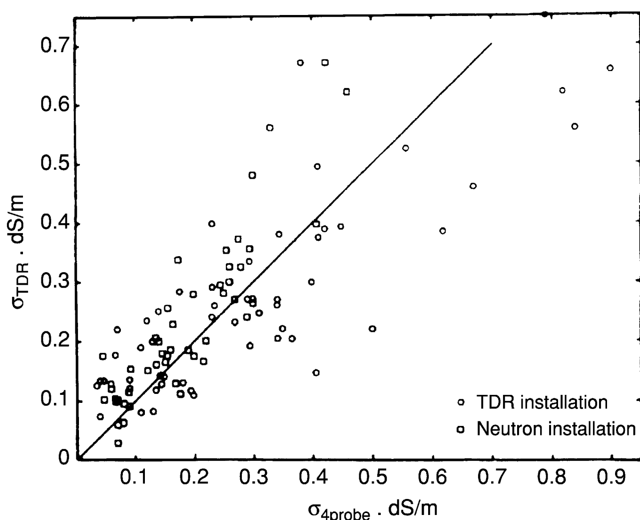


Figure 2 Bulk soil electrical conductivity measured by TDR vs. measurement with four-electrode probe and 1:1 line.

Dasberg and Dalton (1985) published an experimental comparison between $\sigma_{a,\ TDR}$ and $\sigma_{a,\ resistivity,\ 4P}$ (Fig. 2).

Although the data fell on both sides of a 1:1 line (n = 102, $R^2 = 0.68$, which was not too good for one of the simplest measurements), the scatter in $\sigma_{a,\ TDR}$ is 50–150% of the $\sigma_{a,\ 4P}$. Moreover, when σ_a is converted into the desired σ_w, the resulting scatter may be doubled or tripled. Topp *et al.* (1988) compared their method to G-T in both KCl solutions and in two soils and to reference measurements obtained with a conductivity meter and a Wheatstone resistance bridge. They also found that their approach overestimated σ_a by up to three-fold (Fig. 3). Topp *et al.* (1988) suggested that the difference between the methods was a measure of the dielectric loss component.

To explain this gap, Topp *et al.* (1988) mentioned three differences between theirs and Dalton's approach: (i) Dalton assumed that after the signal, which is transmitted into the sample, returns to its point of entry, it is entirely received by the TDR sampler, whereas, in Topp's analysis, allowance was made for additional reflection back into the sample at this point. (ii) Their calculation for the attenuation factor appeared to neglect the time dependence of V_1 and V_2 in that their V_T and V_R were determined at different times. (iii) Dalton *et al.* (1984) used a balun without compensating for the attenuation. Topp *et al.* (1988), unable to get attenuation factor values greater than 1, concluded that Dalton's approach benefited from

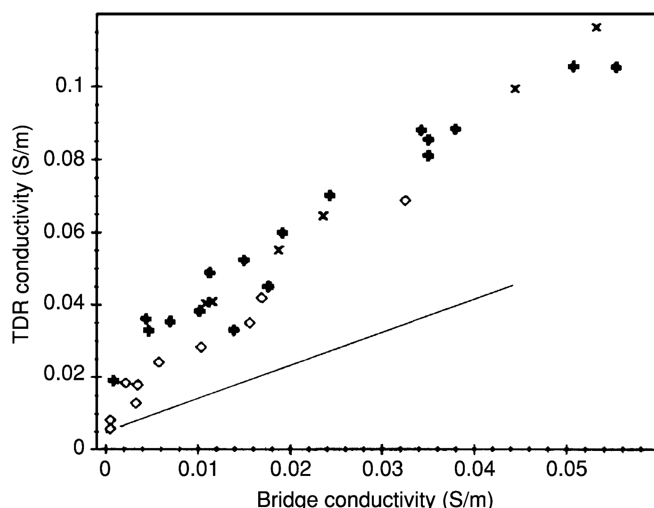


Figure 3 Conductivity of soils measured by TDR vs. conductivity measured by resistance bridge. **X** – Bainesville clay loam, + and ◇ - Rubicon sandy loam.

compensating errors so that this physically impossible situation did not arise. Zegelin *et al.* (1989) also provide experimental data indicating that $\sigma_{a,\ G\text{-}T}$ is more accurate than σ_a (Dalton *et al.*, 1984) (Fig. 2).

Due to these more recently observed disadvantages, research appeared between 1984 and 1987 (Dalton, 1987; Dalton and van Genuchten, 1986; Dalton *et al.*, 1984; Dasberg and Dalton, 1985) which suggested using an attenuation coefficient and the transmitted and reflected amplitudes (Dalton's approach) to calculate σ_a from TDR measurements. However, this approach has not been employed to any great extent.

Therefore, the $\sigma_{a,\ G\text{-}T}$ approach is still currently the most used method for determination of σ_a. Obviously a calculation model that ignores θ altogether, assuming $\theta_{\text{field capacity}}$ (or any other steady-state moisture level) will prevail in the majority of cases, should be avoided as it risks errors (graphically demonstrated in Gupta and Hanks, 1972) of tens or even hundreds of percent (Nadler, 1997).

Although R_L is routinely used in Eq. 3, users should remember that the R_L calculated from Eq. 2 is comprised of the desired probe load (R_P) plus additional contributions (from connectors, relays, and coaxial cables) that have to be substracted for improved accuracy (Heimovaara *et al.*, 1995). This is especially needed under saline conditions when R_P values are low.

The fact that σ_a, obtained by presently common TDR technology and that of the old resistivity techniques are identical (Ren *et al.*, 1999) implies that all the experimental data, calculation models, conclusions, and

σ_a–σ_w relations obtained by the resistivity techniques can be applied when interpreting TDR results.

C. $\sigma_a - \sigma_w$ RELATIONS

σ_a Components and Their Mutual Interaction

σ_a is dependent on the properties **of the soil solid phase**, such as specific surface conductance (σ_s), bulk density (BD), and natural soil structure disturbance during instrument installation; on the **soil's liquid phase**, through σ_w and θ; and the **interaction between them**, through tortuosity (expressed as a formation factor, F); and σ_s fractional contribution to σ_a (δ).

A simple, three resistors-in-parallel model, namely, (i) alternating layers of solution and conductive solid, (ii) ion-conductive solid, and (iii) solution, suggested by Sauer *et al.* (1955), qualitatively interpreted the σ_a of a porous plug (Fig. 4).

Waxman and Smits (1968) have adopted the above model using it to relate the σ_a of a water-saturated sand high in shale to the pore water conductivity (σ_w) and the cation exchange capacity (CEC) per unit pore volume of the rock, with consideration given to the water saturation of the rock.

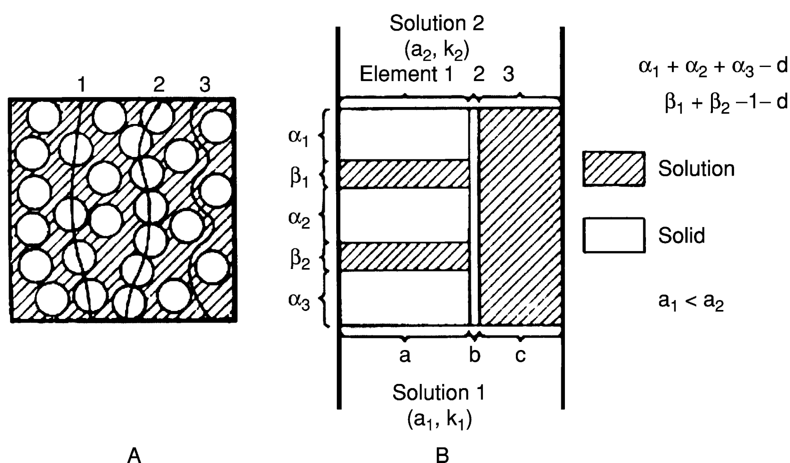


Figure 4 Electrochemical model of porous plug composed of conducting spheres and solution. (A) Schematic representation of current path through plug. (1) represents current through solution and spheres in series, (2) through spheres in contact with each other, (3) current through solution. (B) Simplified model representing situation shown in A.

The three components were presented as:

$$\sigma_a = 1/F * (\delta * \sigma_s + \sigma_w) \tag{6}$$

where F is the formation factor defined as σ_w/σ_a, σ_a, σ_s, and σ_w is the specific conductance of the core (=bulk), clay exchange cations (=surface conductance), and equilibrating solution, and δ – a value between 0 and 1, depending on σ_w and representing the fraction of the maximal contribution of σ_s to σ_a.

The formation factor (F) is defined as the ratio between σ_w of the electrolyte solution with which the pores of the medium are filled and σ_a (corrected for the solid surface conductance), namely, the ratio between σ_w of an electrolyte solution to that of a surficially inert porous medium filled with that solution and which has the same geometry as the actual porous medium of interest. For the sake of explanation, F can be seen as a factor by which the solid matrix reduces σ_w of the pores and solution (Fig. 5).

For the straight-line portion of the conductivity curve:

$$\sigma_a = \sigma_w + \delta * \sigma_s = \sigma_w + f * \mu^e_{Na} * Qc/1000 = \sigma_w + \lambda^e_{Na} * Qv/1000 \tag{7}$$

where σ_s - specific conductance of the clay counter ions (dS m^{-1}), f- Faraday constant, μ^e_{Na} is the maximum Na exchange ion mobility (cm^2/(volt * sec), Qv – is the concentration of exchangeable Na (or any other ions forming the) cations associated with the clay (M L^{-1}), and λ^e_{Na} – is the maximum equivalent ionic conductance of the sodium (or any other forming) exchangeable ions (m M^{-1} dS^{-1}). The intercept of the straight line is σ_s/F, and the intercept is at $\sigma_a = 0$ σ_s (Fig. 6).

Returning to the curved portion of the conductivity curve in the low σ_w, Waxman and Smits (1968) assumed an exponential rise in the counter ions' mobility up to its constant and maximum mobility at higher solution conductivities, based on the conductivity data for synthetic ion-exchange resin plugs (Sauer *et al.*, 1955).

The definition of δ is:

$$\delta = (1 - a * e^{(-\sigma w/\gamma)}) * 0.001 * \lambda^e_{Na} \tag{8}$$

and was introduced to represent the equivalent conductance of the counter ions as a function of σ_w. The value of γ is determined by the rate of increase of the counter ion mobility from that at zero water conductivity up to its constant value at the higher water conductivities. The chemical mechanism explaining this phenomenon is: when a cation exchange resin is immersed in an electrolyte solution it exists as a polymer network of anions and cations of the electrolyte in addition to the exchangeable cations normally present

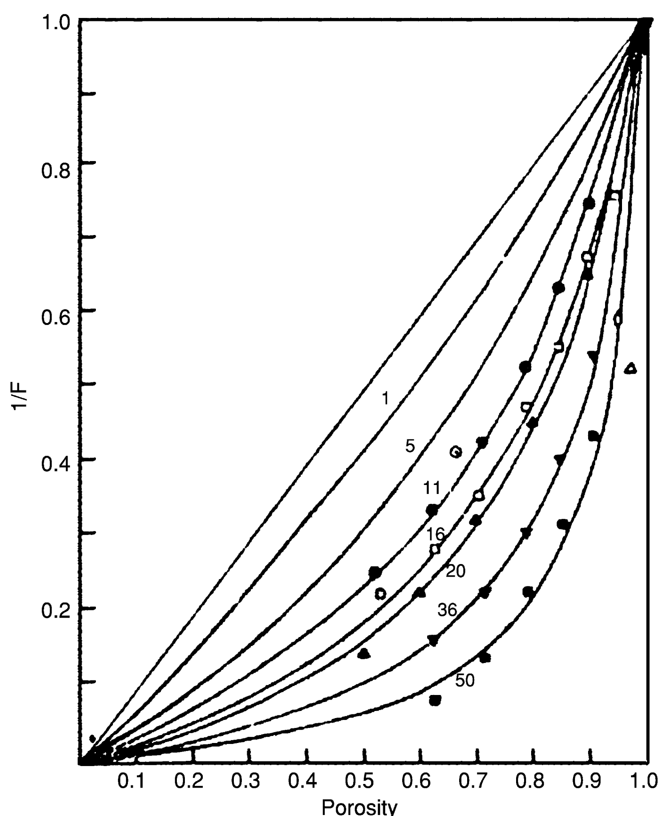


Figure 5 Reciprocal of the Formation Factor (F) vs. porosity. The curves represent Burger's (1919) $F = 1 + k\,(1 - \theta)/\theta)$ equation with shape factor calculated for the axial ratios indicated. ■ – Wyoming bentonite, ▼ - Camp Berteau montmorillonite, ▲ - Zettlitz kaolinite, □ – illite, and ● - Boluvit kaolinite.

(Sauer *et al.*, 1955). The quantity of salt from the electrolyte which migrates into the polymer network of a resin particle appears to be controlled by a Donnan distribution mechanism. Thus, the number of immigrant anions and cations within the network increases with an increase in $C_{\text{external electrolyte}}$. At very low $C_{\text{external electrolyte}}$, the Donnan salt uptake of the soil particles is negligible, but with an increase in $C_{\text{external electrolyte}}$, an increasing quantity of salt enters the network. Thus, the σ of the exchangeable ions is supplemented by the immigrating ions, and in high $C_{\text{external electrolyte}}$ it is therefore necessary to correct the σ of exchangeable ions for the immigrant electrolyte (Sauer *et al.*, 1955).

Similarly, Waxman and Smits (1968) found experimentally and theoretically that in low electrolyte concentrations (0 and up to 0.5 M), $\boldsymbol{\sigma_a}$ **increases**

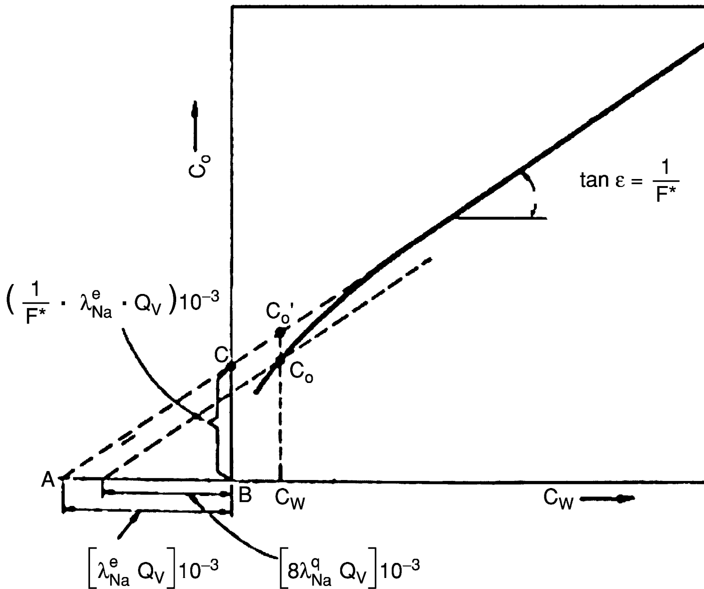


Figure 6 Waxman and Smits (1968) model of σ_a – σ_w relations and its components.

sharply with σ_w at a greater rate than can be accounted for by the increase in σ_w alone. With a further increase in the equilibrating solution conductivity (σ_w) the sand σ_a increased linearly. These findings were discovered in high shale sands with low clay content. The range in σ_a–σ_w nonlinearity is expected for soils with higher clay contents (Fig. 7). The above was experimentally tested by Waxman and Smits (1968) in hundreds of rocks for a wide range of F values (6–150), soil solution salinity (1–23 dS m^{-1}) and water contents (0.04 to saturation). Theoretical and experimental studies from the 1940s to the 1960s have repeatedly proven the existence of σ_s, its non-linear dependence on σ_w, and its contribution to σ_a-σ_w relations when the salinity of the pore waters is low. However, in the1980s and 1990s, when the need for accurate σ_w values increased, σ_s was not emphasized, used as a matching factor, or used as a constant.

σ_s—Electrical Conductance of Solid Surfaces

Using a model of oblate ellipsoids to simulate the shape of clay particles, Cremers *et al.* (1966) reached the same conclusions as Sauer *et al.* (1955). "The linear relationship between σ_a and σ_w can only be expected under a rather limited salinity range and, since σ_s effects play an important role in determining soil σ_a, they must be considered in order to estimate the factor by which the σ_w would have been reduced in the absence of σ_s." σ_s is defined as the specific, integrated electrical conductivity contributed to σ_a by the

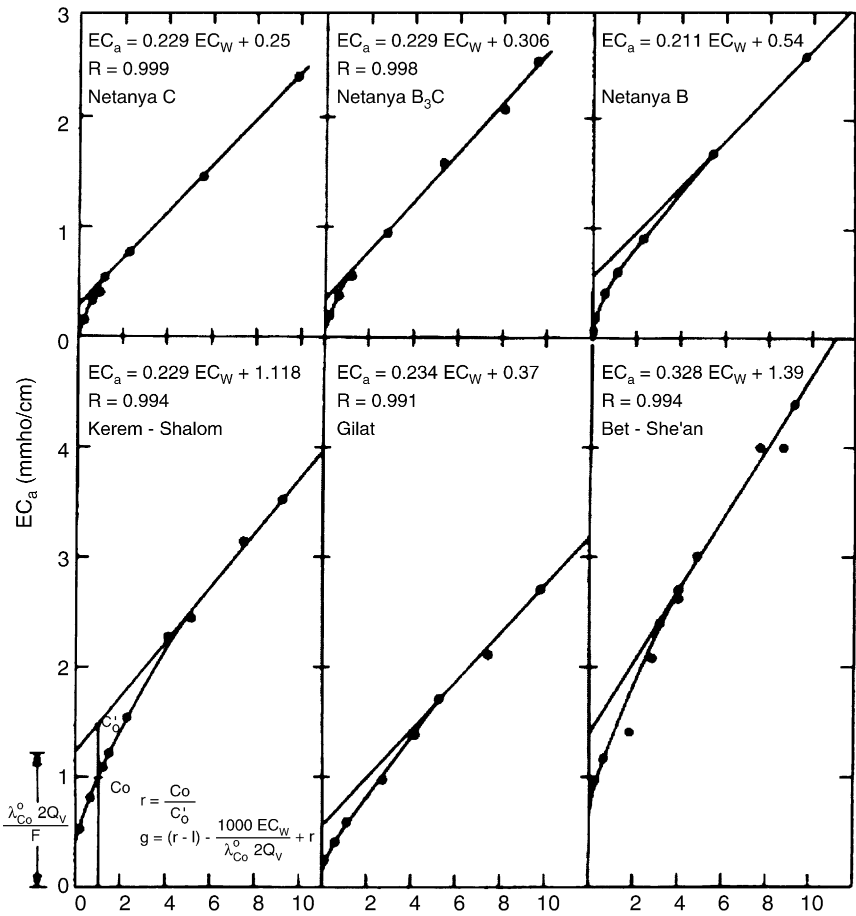


Figure 7 $\sigma_a - \sigma_w$ relations in six different soils. The method of obtaining the needed data for calculating δ is demonstrated.

mobility of the exchangeable ions residing on the soil particle surfaces. The higher the soil clay content is, the higher σ_s, yet its effective contribution depends on bridging by ions in solution between the less mobile exchangeable ions and the actual fraction which will be $\sigma_{s,\ act} = \sigma_{s,\ max} * \delta$, where $\delta = 0$ to 1 depending on σ_w (Fig. 8). In any case, σ_s cannot have values lower than 0.

Adopting the linear model, Risler *et al.* (1996) calculated σ_w and σ_s for three soils during wetting-drying cycles in several experimental soil-packed columns using different σ_{irr} levels. The resulting order of σ_s values (0.07, 0.027, and 0.016 dS m^{-1}) was opposite to that of the soils' texture (very fine sand, sandy loam, and clay loam, respectively), a major σ_s-determining soil

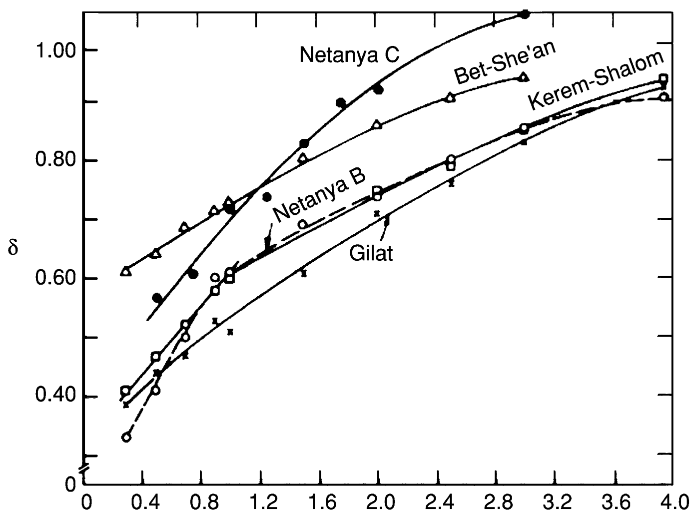


Figure 8 The fractional contribution (δ) of the surface counter ions to σ_a as a function of σ_w and soil type.

property (Petersen *et al.*, 1996). The reason for this unexpected outcome was not explained by the authors but it may stem from the linearity approach, unintentionally turning σ_s into a meaningless correction factor ('hidden' extra degree of freedom?), artificially improving the model results' correlation with the leaching solutions σ_w. A similar outcome, due to the use of the Rhoades *et al.* (1989) model, is reported by Hamed *et al.* (2003) where the model forced the impossibly wide ranges of σ_s values for a single soil (in a typical example: σ_s values from 0.117 to 5.267 dS m^{-1}) and unrealistic negative σ_s values. More on the importance of σ_s, its relevance to σ_a–σ_w relations and errors caused when it is ignored are discussed in Nadler (1997) and Nadler (1999).

Rhoades's model regards the bulk soil σ (σ_a) as two parallel conductors ($\sigma_a = \sigma_b + \sigma_s$): (i) A bulk liquid-phase conductivity σ_b, associated with the free salt in the liquid-filled pores, and (ii) a bulk surface conductivity, σ_s, associated with the exchangeable ions at the solid/liquid interface. Assuming that σ_b depends linearly upon σ_w and that only the fraction of the total cross-sectional area occupied by the liquid phase conducts current, σ_b is expressed as $\sigma_w \theta T$ (where θ is the volumetric water content and T is the transmission coefficient). $T = a + b\theta$ (a and b are empirical constants) accounts for the tortuous nature of the current lines and any decrease in the mobility of ions near the solid liquid and liquid-gas interfaces resulting in:

$$\sigma_a = \sigma_w.\theta * (a + b\theta) + \sigma_s. \quad (9)$$

Soil moisture (θ) changes modify σ_w by varying the amount and composition of dissolved ions, their activity coefficients, and the soil tortuosity. The chances that the lumped effect will maintain linear σ_a- σ_w relations are small. Contrary to the G-T model, Rhoades *et al.* (1976) assumed that for non-sodic soils σ_s does not depend on the salinity of the soil solution (σ_w) nor upon the water content. The validity of these assumptions was tested experimentally by Rhoades *et al.* (1976). They obtained curvilinear relations for σ_a–σ_w because F was non-linearly dependent on θ (Fig. 9). The presentation of the curved part of the relation was smoothed out by stretching the salinity range from 20 to 60 (dS m^{-1}).

Shainberg *et al.* (1980) concluded that the curvilinearity in the low range of σ_w can be accounted for by assuming that the current flows in the soil via a solid-solution series-coupled element, which acts in parallel to the two separate pathways (solid and liquid) included in the model. However, they presented this model in terms of geometric parameters having no physical, chemical, or mineralogical identities.

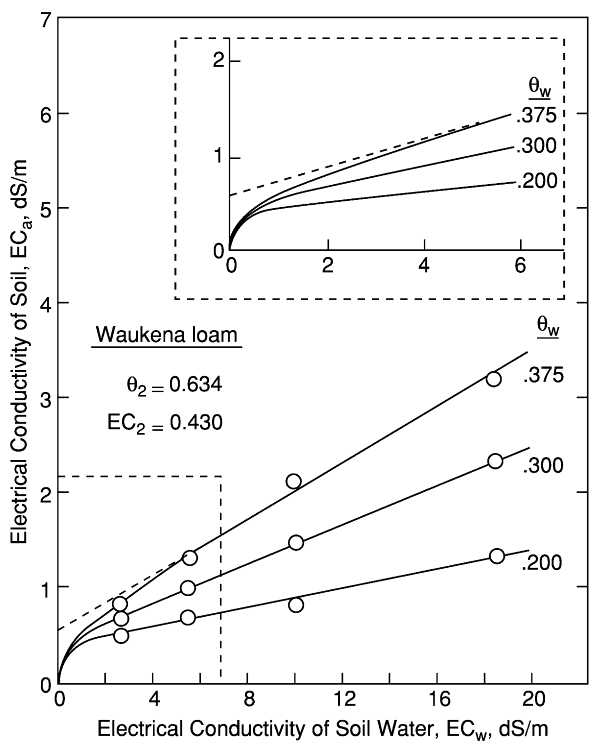


Figure 9 $\sigma_a - \sigma_w$ relations in Waukema loam. The inset expands the non-linear portion of the relations.

Later, in an improved model describing the relations between σ_a, σ_e, and θ that tried to distinguish between the water and salts present in the soil, Rhoades *et al.* (1989) introduced the terms "mobile" (large pores = continuous pathway in soil solution) and "immobile" (fine pores = solution in intraped pores) phases. In their model they attempted to provide a physical meaning to T. Following the model of Sauer *et al.* (1955), it was assumed that the specific σ_a of a soil containing dissolved electrolytes in the soil solution can be represented by a conductance model consisting of three elements in parallel: (i) conductance through alternating layers of soil particles and interstitial soil solution (a solid-liquid series-coupled element), (ii) conductance through or along the surfaces of soil particles (exchangeable cations) in direct contact with one another (the solid element), and (iii) conductance through the interstitial solution (the liquid element). The model is expressed as:

$$\sigma_a = ((a)\,\sigma_{ws}\ \sigma_{ss})/((e)\sigma_{ws} + (1 - e)\,\sigma_{ss}) + (b)\,\sigma_{sc} + (c)\,\sigma_{wc} \tag{10}$$

where a, b, and c, represent the fractional cross sectional areas of the three elements, σ_{ws} and σ_{wc} are the specific σ of the soil water that is in series-coupling with the solid particles and in the separate continuous conductance element, respectively, and σ_{ss} and σ_{sc} are analogous terms for the σ of the solid phase in these same two elements, respectively. Later, no distinction will be made between σ_{ss} and σ_{sc}. Rearranging Eq. 10 by replacing a, b, and c by their θ equivalent, dropping $\theta_{sc} * \sigma_s$ and $\theta ws * \sigma_s$ the model is represented by:

$$\sigma_a = \{(+\theta_{ws})^2\sigma_s/\theta_s\} + (\theta w - \theta ws)\sigma_{wc} \tag{11}$$

which, according to Rhoades *et al.* (1989), is essentially equivalent to the previously unsuitable $\sigma_a = \sigma_s + T * \theta w * \sigma_w$ (where T is the tortuosity) because the model was inappropriate and the real nature of T was misunderstood.

Nadler (1991a) made three comments relating to the part of the model where σ_w <4 dS m^{-1}: (a) The assumptions used in developing the theoretical model do not agree with those applied in the formulation of equations 2 and 4 (in Rhoades *et al.*, 1989, original article), eliminating the physical basis for the suggested model (original Eq. 4). (b) The contribution of σ_s to σ_a can range from 10 to 90% (Fig. 8), depending on salinity, θ, and mineralogy. The σ_s is a critical parameter in determining σ_a–σ_w relations (Ferre *et al.*, 1998). When obtained as a product ($\sigma_a s * \theta ws$) based on unexplained approximations, it created large errors in σ_s (~±30% calculated from their experimental data) that can induce dramatic errors in σ_w. (c) In the final calculation of $\sigma_{w,}$ no clear separation was presented among the specific contributions of the σ_a measurement, soil sampling, clay content determination, and the

mathematical calculations. Rhoades' (1991) response to these comments was consistent with his original arguments and emphasized the successful practical model application.

Mualem and Friedman (1991) tested the experimental results of Rhoades *et al.* (1976) against their theoretical model for predicting σ_w in unsaturated soils and found them to overestimate σ_w by 50–120%, probably due to the overly high values attributed to the water content of the immobile zone at the immediate vicinity of the solid surfaces and also to the tortuosity factor (Fig. 10).

Persson (1997) tested the Rhoades *et al.* (1989) model against his experimental data and found that for non-sandy, heterogeneous soils, site-specific calibrations of σ_a–σ_w relations are needed in order to increase the accuracy due to the model's sensitivity to soil properties. Curvilinear relations between σ_a–σ_w were reported by Winsauer and McCardell (1953),

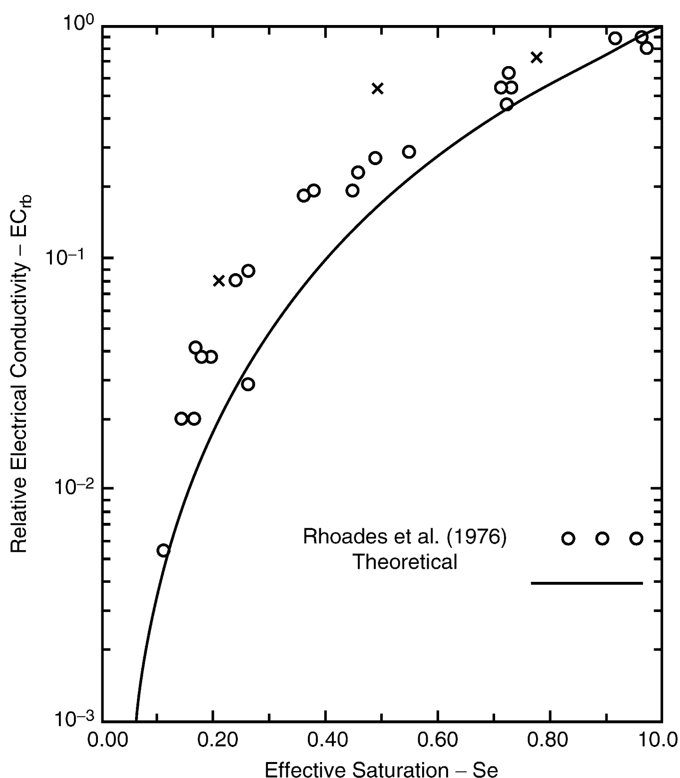


Figure 10 Experimental results and the theoretical curve of the soil relative σ_a (σ_{rb}) as a function of the effective saturation.

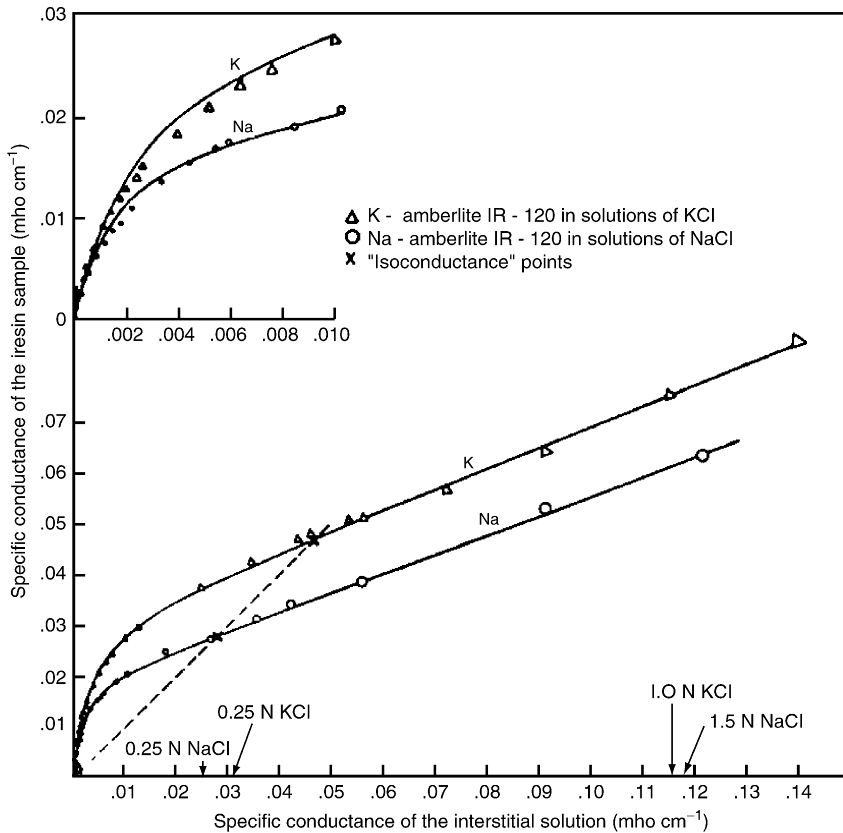


Figure 11 σ_a of resin plug saturated with solution versus σ_w of interstitial solution. O and Δ represent experimental data and solid lines are theoretical curves.

Sauer *et al.* (1955, Fig. 11), Spiegler *et al.* (1956), Waxman and Smits (1968), Rhoades *et al.* (1976), Nadler and Frenkel (1980), Nadler (1981), Topp *et al.* (1988), Rhoades *et al.* (1989), and Mallants *et al.* (1996, Fig. 12).

Regardless of some deficiencies, the Rhoades's model (Rhoades *et al.*, 1976; Rhoades *et al.*, 1989; Shainberg *et al.*, 1980) is undoubtedly the most popular for calculating σ_w from resistivity measurements and soil properties. Rhoades *et al.* (1989) was cited in 79 studies according to Web of Sci. The model is used in several ways: Directly as-is, or adopting its main approach but applying limitations or adding case-specific calibration for comparison with other calculations, or as a starting point for newer models.

A series of three articles, Nadler and Frenkel (1980), Nadler (1981), and Nadler *et al.* (1984), resulted in a calculation protocol based on the Waxman and Smits (1968) model. According to $\sigma_w = (\sigma_a - \delta * \mathrm{In}) * F$ where σ_a was

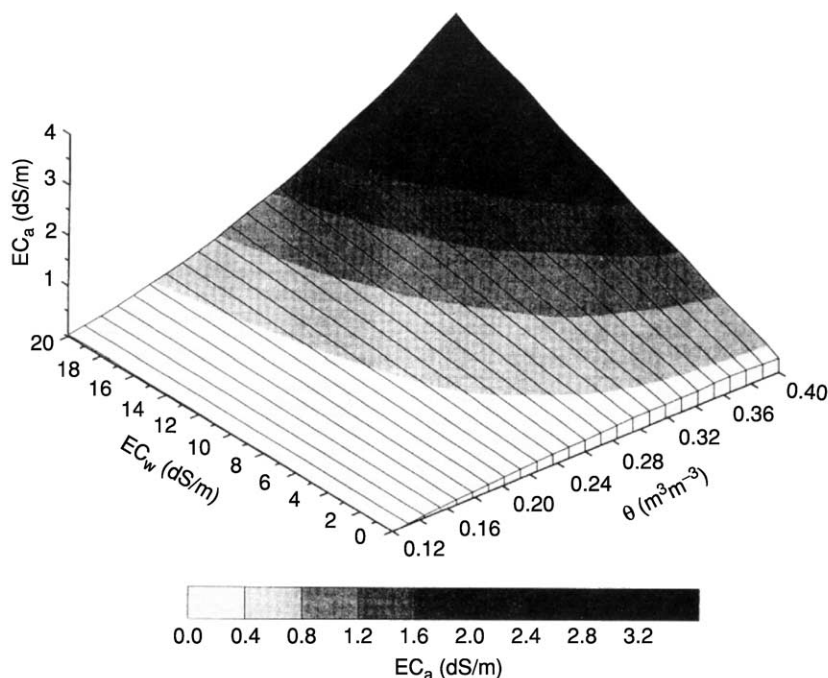


Figure 12 σ_a of Bekkevoort sandy loam soil as a function of θ and σ_w.

obtained (originally from 4EP resistivity probes) by direct measurements, δ is the empirical ratio between equivalent conductance of clay counter ions, to the maximum value of this equivalent conductance (Nadler and Frenkel, 1980), and In ($= \sigma_s/F$) is the intercept of the linear part of σ_a–σ_w curve at $\sigma_w = 0$. The F factor relates the soil's σ to soil texture through the pore size distribution and θ (Fig. 13).

Coupling the determined F-θ relations for soils (Nadler, 1982) with data from Nadler (1981) and Nadler and Frenkel (1980) yielded a "family of curves" of F-θ for different soil textures, represented by percent clay. The percent clay for each sample was calculated from the hygroscopic water content (W_H) (% clay $= 6.92\ W_H - 0.771$, Banin and Amiel, 1969). The parameter In was obtained from an experimentally determined In versus W_H curve (Nadler, 1981; Nadler and Frenkel, 1980). σ_w was calculated by using a small DOS file iterating between the equation parameters: selecting an arbitrary δ, using it to calculate σ_w with which the suitable δ value was determined, repeating the calculation with the new δ, in a loop until satisfying a minimum difference between the last calculated δ value and the one before last. This 20-year-old protocol is offered to the readers upon request. The protocol was applied and tested under various conditions: in a saline

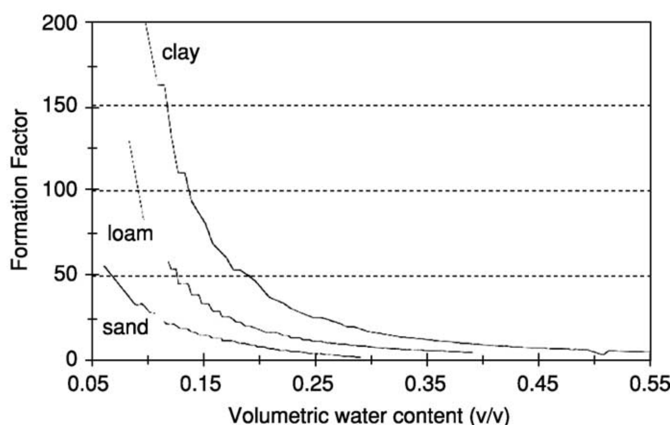


Figure 13 θ dependency of soil formation factor (F) for three soils.

water-irrigated loamy soil where σ_a measurements were still carried out by a resistivity probe (Nadler *et al.*, 1984); in an orange orchard seasonally irrigated with fresh and saline waters (Nadler and Erner, 1998); in three soil types experimentally repacked and brought to different levels of σ_w just by the addition of distilled water (Nadler, 1997); in a loamy soil in a commercial cotton field irrigated with saline water (Nadler *et al.*, 1999); in an apple orchard after a NaBr solution pulse was applied (Vogeler *et al.*, 2001); in a commercial cotton field drip-irrigated at three rates with saline water ($\sigma_w = 3.8$ dS m^{-1}) (Nadler and Ward, 2001); in an artificially layered, repacked soil that was gradually wetted perpendicular to the layering direction by solutions of $\sigma_a = 0$ to 8.4 dS m^{-1} (Nadler *et al.*, 2002); in a sandy soil in a lemon orchard irrigated at three rates (no irrigation, 50%, and 100% of the commercial rate, [Nadler *et al.*, 2003]); and in testing new instrumentation employed in monitoring salt and moisture profiles in a column study (Konukcu *et al.*, 2003). In all cases, the protocol was found to be simple and reliable.

Of the previously mentioned nine examples, one (Nadler and Ward, 2001) deserves special attention for obtaining field σ_w values with an estimated accuracy of ±25% under tough measurement conditions: θ and the dimensions of the wetted soil volume continuously changed below the drip irrigation system. The high salinity of the irrigation water strongly attenuated the TDR EM pulse. High Na^+ content of the irrigation waters enhanced structure sensitivity to salinity.

Although σ_a-σ_w-θ relations are based on F values obtained for disturbed soil samples and their application is then made to natural, undisturbed soils, the readers (as well as users) can rest assured that, in weak-structured soils, when the disturbance is light (plowing) or aggregates under 250 μm

were not broken (Nadler, 1991), soil structure is almost a negligible factor. This soil structure effect was experimentally demonstrated when σ_a was measured in one weak-structured and three well-structured soils under both undisturbed conditions and after structure disruption by two procedures of increasing severity (Nadler, 1991). TDR and the four-electrode resistivity technique were used to measure σ_a. It was found that the σ_a values for undisturbed and disturbed samples were very similar provided that soils were repacked to the original field bulk density. The minimal effect of structure disruption on σ_a is due to the fact that the major change during structure disruption takes place in the macrostructure but is minimal in the more stable micro-aggregate range. Micro-aggregates, 20–250 μm in diameter, are considered stable under rapid wetting, are not destroyed by agricultural practices, and consist largely of particles 2–20 μm in diameter bonded together by persistent organic materials and crystalline oxides.

D. Obtaining F

Of Eq. 6's parameters, F is the most complicated to obtain. The time-consuming process of packing the soil, leaching with solutions of known σ_w, and bringing each soil-solution combination to several θ levels may last between weeks to months, depending on soil texture. A practical method to estimate F dependence on θ that requires only two soil suction values at two separate water content levels was suggested by Nadler (1982, Fig. 14).

F was directly and separately evaluated for the extreme (high and low) θ levels while intermediate range values were obtained by extrapolation. For high θ levels, the Burger (1919) relationship between F, porosity of oblate ellipsoids, and the shape factor were applied by introducing a small modification. θ replaced the porosity, resulting in ($F_c = 1 + k\,(1 - \theta)/\theta$). For the lower water content range, the Brooks and Corey (1964) water content (θ) – water suction (h) relationship:

$$\theta_e = (\theta - \theta_r)/(\theta - \theta_r) = (h_w/h)^{\beta} \text{for } h \; > h_w \tag{12}$$

was used where θ and θ_{sat} are actual and saturated, θ_e is the effective saturation, h is the water suction, h_w is the bubbling pressure, and θ_r is the residual θ, a water content level at which the theory assumes that the effective permeability of the soil to water is zero. The variation of h with changing θ is dependent on the pore size distribution and on the total effective porosity. Plotting $\ln\theta_e$ versus ln h will result in a straight line of negative slope β. Therefore, β is the coefficient relating h and F, assuming that both h and F are similarly dependent on θ. Using h (θ) = a F (θ), the factor a is experimentally determined by two pairs of h for two different θ of

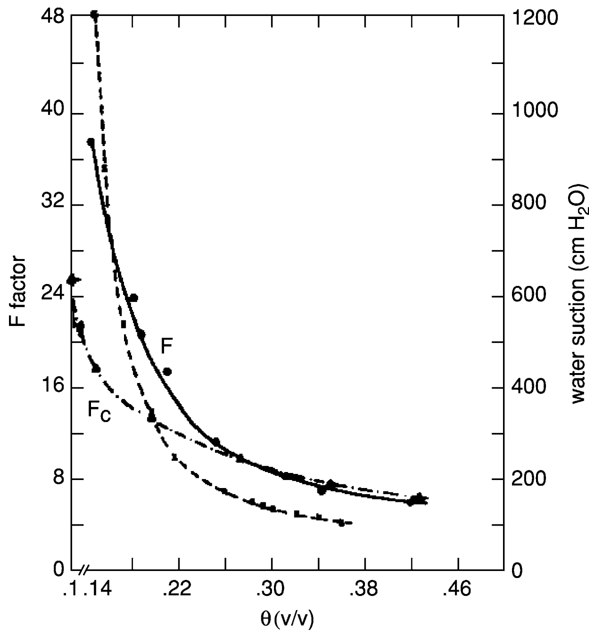


Figure 14 Experimental Formation Factor (F, ●), F calculated after Burger (1919) equation with k=2.38 (Fc, ▲), and water retention curve (X) of Gilat loamy soil as a function of θ.

intermediate and low values. Plotting the ln of the resulting F and $\ln F_c$ against $\ln\theta$ will result in two linear lines which can be extrapolated. Nadler (1982) tested this procedure for four soil types (clay% = 6 to 45) and reported good correlation with experimentally determined F.

E. Additional Protocols for Calculating $\sigma_a - \sigma_w$

(4) Avoiding detailed linking of σ_a to the separate matrix components, Archie (1942) suggested his empirical law:

$$\sigma_a/\sigma_w = N^m = S^n{}_w\Phi^m \tag{13}$$

where S_w is water saturation and Φ is the porosity by which factor he actually "describes" the soil solution "dilution" ("reduced σ") by the solid (rock or soil) while taking into account the water distribution in the matrix pores. The constant n represents the porosity of the matrix (~2 for sandy soils), and m is an empirical exponent dependent on the material consolidation state and degree of cementation. A practical m range in artificially assembled and natural soils and rock is 1.3–2.3. Although successfully

used in pure sands (Ferre *et al*., 1998) discussion of this model is restricted due to its limited use in cultivated soils. The attention of the interested reader is directed to Friedman (2004).

From a pragmatic perspective, using an empirical approach after failing to develop a theoretical basis, a third model was suggested by Hart and Lowery (1998). They assumed that the conductive components act as resistors in parallel and σ_a is the sum of σ soil matrix as well as the product of T and σ_w:

$$Cx = \alpha\sigma_a^{\gamma}\theta^{\delta} \tag{14}$$

where α, γ, and δ are empirical constants, Cx is soil resident x concentration with a typical Cx scatter of 20–35%, and the small error may be explained by the sandy texture (% clay < 1.6).

Recently Amente *et al.* (2000) tested two methods to estimate F: one based on soil hydraulic conductivity (HC) and the other on gas diffusion models. They report a disappointment as they did not see any advantage over the previous methods.

A widely adopted conceptual model proposed by Mualem and Friedman (1991) predicted the σ of bulk soil in saturated and unsaturated conditions. Similar to Nadler (1982), the model is based on the hypothesis that the tortuosity factor affecting σ_a is identical to that defined for prediction of the soil HC. The electrical current in the solution is carried by the ions whose mobility is determined by: (1) contraction of the solution cross section at unsaturation, (2) the distance from the solid face, and (3) specific geometry of the soil solution. Unable to describe it theoretically, they chose a conceptual approach based on the similarity between electrical and groundwater flow. The mechanism behind this similarity is that the flow lines of the water molecules under hydraulic gradient for a given soil and water content are similar to the flow lines of the electric current in the same soil and at the same water content under an electrical potential gradient. The result is equation:

$$\sigma_a = \sigma_w(\theta^{n+2}/\theta_{sat}) \tag{15}$$

where $n = 0.5$ can be used if soil water retention and HC functions are not available for calibration. The best agreement between predicted and experimentally measured $\sigma_{a,\ sat}$ values was obtained when using the results of Nadler (1981). Model testing, using results of seven previous experimental studies on 26 soil samples, showed good prediction under saturated conditions and was satisfactory under unsaturated conditions. The model, satisfactorily tested by Weerts *et al.* (1999), became popular and was applied by many.

Malicki and Walczak (1999) suggested a slightly different, empirical, experimental model, with a threshold θ limitation approach to soil salinity

evaluation based on the derivative of σ_a and ε ($\partial\sigma/\partial\varepsilon$) defined as a "salinity index." Basing their approach on the linear relation between ε-σ_a for $\theta > 0.2$, they calculated soil pore C_{ions} from the salinity index and the soil texture. Errors in directly estimated σ_w (1 to 3 dS m^{-1} and σ_w depending) were reduced to 0.5–1.0 dS m^{-1} by fitting another power function.

(9) Another recent attempt to model σ_a–σ_w A new model of ε-σ_a–σ_w relations using neural networks (NN) was suggested by Persson and Uvo (2003), who reported an RMSE of 0.05–0.13 dS m^{-1} for nine soil types, compared to 0.12–0.87 dS m^{-1} predicted by two traditional models. Typically, a NN acts as a universal function approximator that "learns" a system's output, enabling it to describe larger and more complex systems. In total, 18 NN models were constructed and tested from which one model was selected for each problem and was tested against an independent data set. In all cases, the NN performed better than any other model. Five physical soil parameters were used, but only a sandy soil was tested. Furthermore, the traditional models exhibited larger errors for lower σ_a, and the Rhoades *et al*. (1976) model gave negative σ_w in some cases, whereas the neural network estimated σ_w did not show any trend in the error. Basically, the model seeks to imitate the human brain, functioning by acquiring knowledge through a learning process and finding optimal weights for the different connections among the individual nerve cells; mathematically, the model can be seen as a universal function approximator. The authors claim that by using their model, ε-σ_a–σ_w can be predicted just by using any of several soil physical parameters (sand, silt, clay, and organic matter content, and bulk density) without the need for elaborate soil specific calibration experiments.

Another out-of-scope approach, intended for broad-scale work and adopted by Bohn *et al*. (1982), states somewhat naïvely, "σ_a is similar in principle to σ_w but the non-conductive air and solids cause complications." A resistivity-derived σ_w was found linearly proportional to $\theta * C_{ions}$ over a salinity range of 0–40 dS m^{-1} and a θ range of 0.01–1.5 MPa (Bohn *et al*., 1982). Although the experimental σ_a–θ relations for three soils and a range of σ_w levels gave correlation coefficients close to 0.96, σ_s values for each of the soils were not only strongly dependent on salinity but had extreme negative values (down to –3.32). The authors concluded that soil type did not have an effect on σ_a, even for a clay content range of 6–36%, and that σ_s was insignificant. Still, being aware of these extraordinary results, they justified it by implying that the wide range of salinity swamped out the soil-specific effects.

(11) A quite unique combination of model and sensor for $\sigma_{w,\ pore\ water}$ (Sigma Probe) "suitable for a broad range of soils, and θ_{soil} between 0.1 and saturation, of pore water up to 3 dS m^{-1}," was developed by Hilhorst (2000) and initiated during his Ph.D. studies (Hilhorst, 1998). Because the electrical permittivity and conductivity of the bulk soil area are a function of the

permittivity and conductivity of the pore water, Hilhorst (2000) assumed that at $\theta > 0.1$ both functions are equal and, thus, by simultaneously measuring permittivity and conductivity of the bulk soil, σ_w can be calculated. The protocol is based on several approximations: The hypothesis that σ_w of the pore water and the extracted water are the same ($\sigma_{w\ pore\ water} \approx \sigma_{w\ extracted\ water}$), that ε_{dp}'' (imaginary component of the dielectric loss of the pore water) is negligible for frequencies common to most conductivity sensors, and that $\varepsilon_p \approx \varepsilon_p' - j\ \sigma_p/\omega\varepsilon_0$. But the most likely major error source comes from describing the soil-specific σ_a–σ_w relation, or more specifically, from the geometric factor and the tortuosity expressed in the factor defined as the $\varepsilon'_{\sigma b\ =\ 0}$, offset to ε_a. Hamed *et al.* (2003) compared the results of σ_w measured by the Sigma Probe and TDR in nine different soil types with $\theta = 0.05$–0.50 and three σ_w values: 0.3, 1.2, and 3.0 dS m^{-1}. Using an offset value of 4.1 gave σ_w that were 20% (but can be as high as 40%) of the true $\sigma_{w,}$ when $\sigma_w > 1$ dS m^{-1}, and the error for $\sigma_w < 1$ dS m^{-1} can be much larger. From the observations that (i) different soils fit differently, (ii) different soils have different lower operational θ, (iii) the results could be improved by using a soil-specific offset value, and (iv) the need for negative offset values, it can be concluded that the sensor is still not fully independent of θ and soil type.

III. CONCLUSIONS

Knowing salinity level may be useful in many plant-soil-water studies such as marginal water irrigation, deficient irrigation, irrigation under high ET conditions, plant salt tolerance, salt or water mass balance, or determining salinity threshold values for yield loss. Presently, there is only a limited use of the classical methods for measuring salinity: (i) inductive remote sensing methods (no direct contact between sensor and measured medium), (ii) suction cups, and (iii) drainage water analysis when possible (e.g., when plants are grown on detached root-beds in greenhouses) but mainly (iv) soil sampling and aqueous extracting.

The main disadvantages of the preceding four methods are that they affect the natural equilibrium, thus distorting or poorly representing it, and are labor intensive. These limit their wider and satisfactory use in field salinity evaluation.

While there are acceptable situations where the above salinity evaluation methods (remote sensing, suction cups, and aqueous extracts) can be used with a relatively high degree of confidence, there exist combinations of measuring methods and soils that distort the natural situation. These should be recognized, acknowledged, and avoided (or at least taken into consideration).

Remote sensing methods for σ_a measurement may depend on a dozen or more parameters, and in most cases there is insufficient data to isolate the desired σ_w component from them. Obviously, not requiring direct contact, inductive remote sensing methods are most suitable for mapping large areas of massive salt infiltration. However, within the practical agriculture range limit of this review, the expected accuracy is too low, and its application is rather limited. Tests made to improve the accuracy of results by integrating such local, random, direct calibrations with remote sensing were still not good enough for application to a single orchard or plot. Suction cups can supply reliable soil profile salinity data if properly installed in the soil and if activated systematically with respect to irrigation events. Unfortunately, the method demands intensive labor, and there is quite a wide range of θ when a sample cannot technically be obtained.

The most common method for salinity evaluation is soil sampling and aqueous extraction (saturated paste, 1:1 soil:water ratio, and sometimes up to even 1:5). The weakness of this method (Fig. 15) stems from two processes triggered by the addition of water: (i) dissolution of slightly soluble salts (lime, gypsum, phosphates) that are solids in the natural situation and therefore would not contribute ions to the electrical conductance (ii) and combined with this artificial contribution of ions, dilution changes the natural chemical equilibrium between the ions in the pore solution and the exchangeable ions on the surfaces of solids. Typically, the pore solution Na/Ca ionic ratio is affected. Therefore, the user of this method should be aware of the measurement conditions: The sandier the soil is, the wetter it is during sampling, the more leached of salts it is, and the lower the content of slightly soluble minerals—the smaller the difference between the natural and the disturbed state will be. At the other extreme, for a silty or clay soil with high salt content, which is drier and contains carbonates, sulfates, or phosphates, the larger the gap between the natural and analysis states will be.

Consequently, when higher accuracy is needed, using an electrical σ–ε dual-methods instrument is recommended. It is therefore surprising that the σ–ε dual approach is not the automatic choice, as it is not only the most accurate but also independent of the system parameters.

Complexity of operation: The Cable Tester/TDR family of instruments (Tek1502, Campbell [TDR-100], Trase, or Theta-Probe by Delta-T Devices) are not as simple to operate as the neutron moderation or the resistance probe. Even so, with a short and intensive training course including demonstrations and hands-on practice, operators can qualify in no more than a week.

Price: An expenditure of about US$12,000 is a burden on most budgets. During the long period that Tektronix dominated the market with the Tek1502 Cable Tester, its high price (~US$12,000) seemed to many to be

prohibitively high for research purposes, let alone for direct agricultural production. However, this attitude did not take into account the fact that the 1502 has a service life of at least 10 years (personally I own an 18-year-old Cable Tester that still functions well), thus reducing the average annual cost to a tolerable level. Nevertheless, the user still faces the huge initial investment.

Means for characterizing soil type: An indicator for characterizing the soil type with respect to the bulk soil σ (the issue at hand), which is both reasonable and common, is the soil's texture as expressed by its clay content. The rationale is, of course, the direct contribution of the exchangeable ions residing on the clay surfaces to the total bulk σ. In montmorillonite and kaolinite, a good correlation between percent clay and specific solids surface area, $\theta_{saturation}$, $\theta_{field\ capacity}$, or $\theta_{air\text{-}dry}$ was reported (Banin and Amiel, 1969) for a compilation of 70 soils. However, this is still a weak point in the method. The scatter of the correlation is wide and, from the point of view of minerals present in soil, the Banin and Amiel (1969) database is extremely limited, not representing volcanic, vermiculite, or organic soils. The complexity of the σ_a-σ_w relations is further demonstrated by the present author's failure (unpublished data) to put together, in a single figure, σ_a–σ_w relations reported in 26 studies published by different authors in which θ levels and soil texture could be evaluated. This goal could not be accomplished because too many curves crossed each other and, even worse, the logically expected order of curves, related to the soil texture, was not present. An intensive study should be carried out to test one or more indicators that will characterize the soil textures for the main groups of soils globally.

What should be done in order to promote the σ–ε dual approach?

1. The first step should be to develop awareness of the NEED for an accurate measurement of the distribution of salinity down the soil profile. Farmers, extension service people, and scientists should be exposed to this important source of information.
2. Promotion of current and future σ–ε dual methodology. The new σ–ε generation of instruments, some still under R&D (Nadler and Lapid, 1966), some already in prototype form as described by Ruth (1999), Hilhorst (2000), and A. S. Benet, Almeria, Spain (personal communication, http://www.eeza.csic.es/eeza/i_sbib.htm), promise a sharp price decrease while still maintaining the unique qualities of this method of measurement. These devices attempt to harness the new generation of high frequency (RF) components that became increasingly popular with the spread of cellular phones which operate in the same frequency range. The 1502 (and its descendants, such as TDR-100 or Trase) use a technology called "sampling scope" that enables a measurement of a very short duration signal to be made in a time period that is 1000 times longer. The "sampling scope"

technology divides the too-short-for-measurement signal into 1000 slices, measures each separately, and then reassembles the separate pieces back in place so fast that the operator does not notice the process occurring. This ingenious tool is expensive and does not permit a reduction in instrument prices. Recent R&D efforts are aimed at substituting this expensive technology, and we can expect that sooner or later it will be found.

3. Adding an electrical conductivity feature to the capacitance measurement. Because σ measurement is easy and cheap (not more than a few dollars), once the ε can be successfully measured, the σ component will be attached to it to form an inexpensive, accurate, and simple-to-operate σ-ε dual instrument. It is anticipated that the new σ-ε instruments will be an order of magnitude cheaper. Also, according to the methodology reported in the previous paragraphs, software will be written to interpret θ, σ_a, and an additional input that will identify the soil type, and which will enable real-time, accurately calculated σ_w values.

Following is an example demonstrating the unique advantage of the σ–ε dual method when studying irrigation efficiency.

A direct reciprocal correlation exists between irrigation efficiency (expressed as the Leaching Fraction, LF), depth, and amount of salts accumulating in the soil profile. An accurate estimate of LF values is not easy due to the heterogeneity of the irrigation water distribution (especially in drip irrigation), variability in soil texture, layering, and the spatial distribution of roots. Actually, one is trying to integrate an infinite chain of transient situations with insufficient measurements. In such a situation, the dual σ–ε measurement may be helpful. In contrast to the θ, salt accumulation with decreasing LF is integrative and therefore easier to quantify. The advantage of the TDR method (or the σ–ε dual method in the future) is that, with no extra effort, both properties are measured simultaneously, by the same instrument, in the same soil volume, and are complementary during data interpretation. This way we get two independent measurements looking at and reporting the same phenomenon. Soil solution movement is in the soil profile. In a practical application of this, Nadler *et al.* (2003) calculated σ_a and θ from TDR measurements in five-year-old lemon (Citrus lemon (L.) Burm. F trees in a semi-arid region (Israel) orchard which was irrigated at 100, 50, and 0% of the regional common practice (typically 600–800 m^3 $month^{-1}$ ha^{-1}). Four irrigation treatments were established to deliver (i) normal or 100% (full), (ii) half of normal to one side of the tree (50%), (iii) half of normal applied to alternate sides (with three-week intervals) of the tree (split), and (iv) 0% (dry). Treated sewage water ($\sigma_w = 0.9$ dS m^{-1}) was used to irrigate the trees for 75 days (end-June and mid-September). Changes in θ_{soil} were monitored at weekly intervals. (More details can be found in Nadler *et al.*, 2003.) Figure 16 shows the timeline of θ_{soil} and σ_w for the four

irrigation treatments, as measured before and during the stress imposing period. Most of the θ values fell in the range 0.08–0.16 with extreme values between 0.05 and 0.18. As expected for a very sandy soil, the range of θ_{soil} is quite narrow, and the extreme values of the different treatments are quite similar.

In each of the irrigated treatments, θ_{soil} clearly showed periods when θ increased following a series of irrigation events. In contrast, θ_{soil} of the "dry" treatment showed a fairly steady decrease over the whole water stress period. In absolute terms, there was, as expected, more water stored in the root zone of the fully-irrigated trees compared to the dry trees; intermediate levels of soil moisture were recorded in the root-zone of trees in both the "50%" and 'split' irrigation treatments.

Using the Nadler *et al.* (1984) protocol, σ_w values were calculated for the undisturbed soil pores solution, based on the TDR measurement of bulk soil electrical conductivity, σ_a, and the water content and texture of the soil. It can be seen (Fig. 16A) that within the depth range 0.1–0.7 m, most of the σ_w values in the "full" treatment are consistent and similar to the salinity of the irrigation water (0.91 ± 0.2 dS m^{-1}). However, beyond a depth of 0.7 m, the values of σ_w increase to about 3.0 to 4.0 dS m^{-1}. The depth of leaching

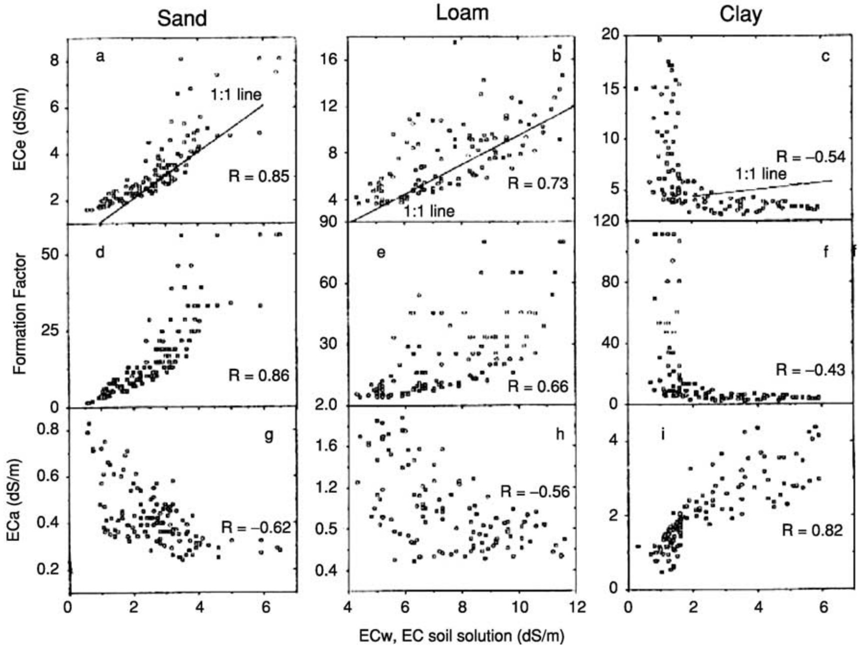


Figure 15 θ-adjusted 1:1 aqueous extracts (σ_e) (a, b, c), soil formation factor (F: d, e, f), and σ_a (g, h, i) vs. σ_w for sand, loam, and clay soils, respectively.

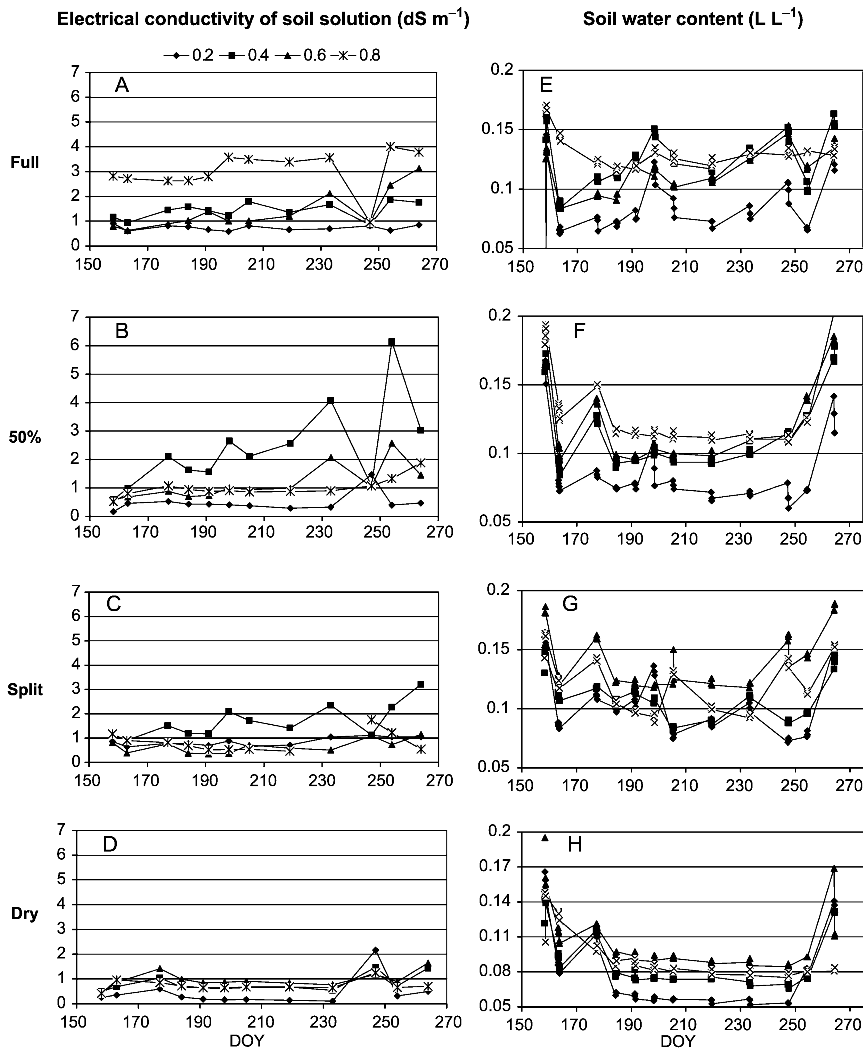


Figure 16 Seasonal changes of soil moisture content (θ_{soil}) and salinity of the soil solution (σ_w) for the "full," "50%," "split," and "dry" irrigation treatments. DOY refers to the Day of Year. All the measurement were obtained with 200 mm-long probe installed vertically at .1–.3, .3–.5, .5–.7, .7–.9 m, except in the "split" where depths of probes were 0.3–0.5 and 0.5–0.7 m, on both sides of the tree.

for the "50%" irrigation treatment (Fig. 16B) is much shallower because only half the amount of water has been applied. The TDR measurements of σ_W indicate that some water may still be leaching down, out of the upper 0.5 m of the soil profile, since a small increase in salinity was recorded in the

deeper soil layers. All values of σ_w from the "dry" treatment are similar to those of the irrigation water (~1.0 dS m^{-1}, 16D). On DOY = 247, a sharp decrease in σ_W is seen, explained by the intensive dilution due to the very recent irrigation event. A week later (on DOY = 254), the σ_W level increased once more after enough time allowed for evapotranspiration.

The TDR measurements of soil moisture in the upper 1 m suggest that some surplus irrigation was applied after about DOY = 220, since θ_{soil} slowly increased for all irrigated treatments soon after that day (Fig. 16E). There were also periods of water accumulation in the different soil layers but the length of these periods declined time. It is also clear from Fig. 16 ("full," '50%," "split") that the root uptake activity is greatest from the surface roots. The largest decreases in θ_{soil} are recorded by the TDR probes at depths of 0.1–0.3 m. Root uptake activity by the deeper roots, at depths of 0.7–0.9 m, is smaller than in the layers above it.

The gradual increase in θ_{soil} measured for the "full" and "50%" treatments suggest that irrigation was applied at a rate that exceeded the tree's requirements (Fig. 16E, F). Thus, it is possible that the farmer over-irrigated in this period, and that some water could be saved. Over-watering is further supported by the TDR measurements of soil water salinity, σ_W [dS m^{-1}], made during the water stress period. Over the depth intervals 0.1–0.7 m, most of the σ_w values in the "full" treatment are consistent and similar to the salinity of the irrigation water (0.91 ± '50%', dS m^{-1}). However, beyond a depth of 0.7 m the values of σ_w increase to about 3.0–4.0 dS m^{-1}. The salinity increase with depth is consistent with leaching of salt out of the upper 0.7 m of the profile, and it suggests a salt accumulation below this depth. The depth of leaching from the "50%" irrigation treatment is much shallower because only half the amount of water has been applied to these irrigated trees. The TDR measurements of σ_w indicate that some water may still be leaching down, out of the upper 0.5 m of the soil profile, since a small increase in salinity was recorded in the deeper soil layers. All values of σ_w from the "dry" treatment are similar to the irrigation water (~1.0 dS m^{-1}); no additional salts (or water) were added to the profile. Measurements of θ_{soil} and σ_w by vertical TDR probes at this site could be used to adjust the LF as required.

SUMMARY

A short introduction to the principles of calculating σ_a from resistivity and TDR were presented. A series of procedures aimed at calculating σ_w from σ_a, θ, and soil properties were then presented. The potential user is invited to knowledgeably select whatever he finds most suitable according to his needs, available data, and satisfactory accuracy.

Less recommended approaches are those using commercially available σ_a sensors (e.g., Geonics EM38), especially when not accompanied by θ and texture measurements.

Extra caution should be applied when ascribing conclusions based on σ measurements carried out in solutions to solid-liquid combinations (e.g., wet soil [Topp *et al.*, 1988] or wet botanical material) because the latter may filter the frequencies of which the EM pulse is composed and thus change its interaction with the investigated medium.

It should be kept in mind that σ_s represents a real physical phenomenon and cannot therefore be assigned negative or constant values. It should correlate with the soil texture, and its actual contribution to σ_a should depend on the salinity of the soil solution at certain (low) levels. On the other hand, if $\sigma_w > 4$ dS m^{-1}, the σ_s dependence on salinity can be ignored and if $\sigma_w > 8$–10 dS m^{-1} and the soil is wet, σ_s can be ignored altogether.

Salinity levels estimated by aqueous extracting of soil samples and by resistivity measurements do not fully overlap and therefore calibrations originating from either source should not be mixed.

Aside from TDR's many advantages, we cannot ignore its user-unfriendliness. Easier and wider adoption may be achieved by (i) simplification of the operating system, instrumentation and, software, (ii) reaching an expression for σ_w similar in qualities to Topp's equation for θ; this will simplify and unify σ_w calculation while giving up only a little in accuracy; (iii) replacing the expensive cable-tester (or its equivalents) with small, simple, and inexpensive dual resistivity-capacitance sensors.

Applying the Nadler *et al.* (1984) protocol to calculate σ_w is recommended to the readers on the basis of more than a decade of satisfactory use (see Section: σ_a–σ_w Relations, Item #3). Potential users can adopt the approach format only and then fill in their own coefficients according to their soils' properties (water retention, mineralogy, pore size distribution). Others may request from the author and receive (by e-mail) the current version which originally was uniquely intended for the montmorillonite-kaolinite soil types predominant in Israel. If no soil specific adjustments are made the users risk obtaining output that may be extremely inaccurate (which is advantageous because larger errors are easier to detect), unrealistic σ_w (obviously to be discarded), or the software may refuse to process the data.

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THE SUSTAINABILITY OF IRRIGATION

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I. INTRODUCTION

Irrigation is the supply of water to agricultural crops by artificial means, designed to permit farming in arid regions and to offset periodic droughts in semiarid regions. Even in regions where total seasonal rainfall is adequate on average, it may be poorly distributed during the growing season and variable from season to season. Wherever traditional rain-fed farming is a high-risk enterprise, irrigation can help to ensure stable production.

Irrigation has long played a key role in feeding expanding populations and is expected to play a still greater role in the future. Although irrigated land amounts to only some 17% of the world's cropland, it contributes well over 30% of the total agricultural production. That vital contribution is even greater in arid regions, where the supply of water by rainfall is least

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and the demand for water imposed by the bright sun and the dry wind is greatest.

Areas where irrigation is a precondition for profitable farming are those that receive insufficient rainfall, on average, to sustain dry-land farming (the minimum for which is usually 300 mm of cool-season rainfall or 400 mm of warm-season rainfall). Where rainfall is low and sporadic, periods of drought tend to be longer and more severe. It is this discrepancy between the evaporative demand for water and the limited natural supply of water that makes irrigation an imperative in semiarid and arid regions. Once irrigation is assured, many such regions can produce bountiful crops, thanks to favorable temperatures, abundant sunshine, and —especially in river valleys—deep and fertile soils.

Irrigation can do more that merely raise the yields of specific crops; it can also prolong the effective crop-growing period in areas with extended dry seasons, thus permitting multiple cropping per year where only a single crop could be grown otherwise. With the security provided by irrigation, additional inputs needed to intensify production further (e.g., pesticides, fertilizers, improved varieties, physiological treatments, environmental controls, soil amendments, and tillage) may become economically feasible. Irrigation reduces the risk of such expensive inputs being wasted by crop failure resulting from lack of water.

The practice of irrigation consists of applying water to the part of the soil profile that serves as the root zone, for the immediate and subsequent use of the crop. Inevitably, however, the initiation and the continuation of irrigation in a given area induce a series of processes that can profoundly affect both the on-site and the related off-site environments, and not necessarily for the better. Over time, some of its potentially self-destructive effects may make the very practice of irrigation unsustainable.

For some years now, even as great investments have been made in the development of new irrigation projects, the total area under irrigation has hardly grown. The causes for this situation are various. In some cases, the water resources upon which irrigation projects depend have been depleted, polluted, diverted to other uses, or have become subject to intensifying disputes among competing economic or political sectors or national states. In many other cases, large tracts of irrigated land have degenerated to the point of being rendered uneconomic to continue cultivating, or—in extreme cases—have become totally sterile. The dilemmas of water-resource deterioration and of land degradation are not exclusive to the less-developed nations, where they have resulted in repeated occurrences of famine. They apply no less severely to such technologically advanced countries as Australia, the United States of America, and the central Asian regions of the former Soviet Union.

So widespread, pervasive, and inherent are the problems associated with irrigation that some critics have come to doubt whether irrigation can be sustained in any one area for very long—and they have much evidence to support their pessimism (Letey, 1994). However, the historical record of irrigation schemes varies widely among the different climatic zones of the world. Whereas irrigation schemes in the more humid climes, such as are found in Indonesia or Southern India, look back at thousands of years of irrigation, such longevity in drier regions of the world is the exception rather than the rule. Herein, we examine the facts in search of the possibilities of and constraints to sustained irrigation based upon clear recognition of the problems, the environmental conditions under which they are most prevalent, and the measures necessary to alleviate them.

The concept of sustainability is itself somewhat problematic. A dictionary definition is "being capable of remaining in existence, and of functioning, continuously and indefinitely." In the past, knowledge was too limited for people to foresee, let alone forestall, the eventual consequences of the way in which the environment was manipulated. At present, we know much more about the processes involved, and we have the technology to cope with some problems formerly considered uncontrollable. Although our knowledge is still incomplete and much remains to be researched, what we do know presents us with an opportunity and a challenge to avoid practices likely to cause degradation and to promote practices likely to maximize the probability of long-term success.

Is irrigation sustainable, and if so, where, how, and under what conditions? The question should address both the on-site and off-site aspects of sustainability. Any attempt to answer this question requires assembling and organizing the disparate facts, combining the agronomic, hydrologic, environmental, and economic facts and principles into a coherent overview. The ultimate aim must be to help policymakers to understand the tradeoffs and conflicts between direct beneficiaries and the up- and downstream stakeholders. This should help them adopt and enforce measures capable of ensuring the long-term viability and productivity of irrigated agriculture in the different climatic regions around the world.

II. OFFSITE ENVIRONMENTAL ISSUES

The first requirement of an irrigation project is the availability of a dependable supply of fresh water and the means for its delivery to the site to be irrigated. The second requirement is the availability of suitable land at that site upon which to grow the crops under irrigation. The third requirement is an outlet for the safe disposal of wastewater from the irrigated land.

Every irrigation project therefore consists of withdrawing water from some natural source (a lake, an aquifer, or a river) and diverting it to the site (herein referred to as the "onsite") of irrigation. In the process, inevitably, that water is denied to some other site (an "offsite"), to its ecosystem, and to the human population that had been its prior recipients.

In the typical case of a river valley project, changes take place in both the upstream and downstream sections of the riverine domain. River flow is generally time variable. More often than not, the season of peak irrigation demand coincides with the period of low river flow. Hence, an irrigation project typically requires the construction of engineering structures—dams and canals—designed to regulate the flow so as to ensure adequate storage and supply throughout the growing season. The scale on which this may be done can vary by several orders of magnitude. Whereas irrigation schemes servicing tens or hundreds of thousands of hectares are not unusual in Asia, small perimeters of 20–50 ha are increasingly common in sub-Saharan Africa. Though the investment per hectare may be comparable, the environmental costs and stakeholder conflicts may be disproportionately higher and less manageable in the megaprojects.

Dam construction is a problem in itself. Appropriate locations for dams are relatively rare. The ideal topographic, geologic, and climatic conditions are seldom found in the proximity of target irrigation projects, and less than ideal conditions may make the construction and maintenance of dams economically prohibitive and environmentally unsustainable. Unfavorable topography may require massive and expensive construction and may result in the submergence of very large areas with consequent damage to natural ecosystems, displacement of long-established human populations and infrastructure, and loss of cultural heritage and scenic sites. Some areas are inherently vulnerable to potential natural disasters such as earthquakes. Porous or fractured substrata may cause great losses of water by uncontrollable seepage, and a dry climate may impose additional loss of water by direct evaporation. A case in point is the Aswan Dam and its Lake Nasser, located in the midst of the earth's driest desert, where evaporative losses of water may be in the range of 10–16 billion cubic meters per year—as much as 20% of the inflow (Hillel, 1994).

Future development of water resources is constrained by additional factors. Most of the favorable water-storage sites that were available and could be developed readily at relatively low cost have been utilized. Some of the proposed new dams and reservoirs are either too remote, entail large costs of construction and maintenance, or are likely to cause damage to the environment or to culturally important sites of present or past habitation. At the same time, competition for public funds has intensified everywhere.

For these and other reasons, recent years have witnessed a growing popular resistance to the construction of dams, particularly of large dams.

That sentiment, reinforced by economic considerations, has contributed to the reluctance of international funding agencies such as the World Bank to invest in large dams to the degree that they had invested in such projects previously. Examples of controversial dam projects include the Narmada Dam in India, the series of dams built on the headwaters of the Euphrates and the Tigris as part of Turkey's Eastern Anatolia project (GAP), and China's huge Three Gorges project. However, recognizing the need to double food production over the coming few decades, the financial institutions are now reassessing their attitude toward dam projects. The expansion of irrigation around the world in the future is likely to be affected by this pendulum, seeking irrigation expansion while minimizing offsite costs.

Additional loss of water by evaporation, and especially by seepage, occur in the system of conveyance over distance from a dam to the site or sites of irrigation. Generally, this conveyance takes place via canals and ditches, which—in the interest of minimizing costs—are often dug into the ground and left unlined (i.e., not underlaid with concrete or other impervious and scouring-resistant material). Even where closed conduits (i.e., metallic, ceramic, or concrete pipes) are installed, they tend in time to develop leaks and to incur considerable loss of water and hydraulic pressure.

Water storage behind dams is also subject to the insidious process of silting, which—gradually, over a period of some decades—reduces a dam's capacity and may eventually clog its storage basin entirely. Extending the lifetime of a reservoir calls for erosion control measures upstream, often labor intensive or expensive interventions that are demanded from those who do not immediately benefit from the water storage. Without it, silt accumulation in reservoirs and canals will be especially rapid in regions where the upper watersheds of the rivers have been denuded of their natural vegetative cover by overgrazing and further destabilized by excessive cultivation, thus subjecting the catchments to accelerated soil erosion. These processes of ecosystem and land degradation are particularly widespread in semiarid and arid regions, and are often referred to by the term "desertification."

Thus far, we have considered environmental processes that may take place upstream of an irrigated area. In addition, irrigation entails a series of processes that occur downstream. The first of these is the diminution of the river flow resulting from the abstraction of the water used for irrigation. The abstraction of water affects communities downstream directly and indirectly. The direct effect is the deprivation or reduction of water for agriculture or for other sectors of the economy. If water is occasionally released from the reservoirs for energy production, it often is available downstream during periods of low demand. A typical example is the off-season release of Amudarya water by Tadjikistan in winter months for heating purposes

when it can not be used effectively by other riparian states. If released for irrigation, downstream users will generally receive lower-quality water.

Indirect consequences for communities are due to environmental changes when downstream riparian ecosystems along the riverbanks, floodplain, and estuaries are deprived of vital water supplies and thereby impoverished. Natural wetlands that were originally biologically diverse and highly productive may be subject to periodic or permanent desiccation, and even to the eradication of vital species or biotic communities. What happens to estuaries also tends to impact near-shore marine habitats, especially fisheries. Where a river discharges naturally into a freshwater lake, the deprivation of the lake's inflow resulting from the river's diversion for irrigation may cause the lake to shrink markedly, and sometimes drastically. The shrinkage of the Aral Sea in central Asia is a prime example of the sort of environmental and human disaster that can be caused by large-scale irrigation development. The shrinkage of the Dead Sea (shared by Israel and Jordan) is another example.

These environmentally damaging processes and their effect on humans are greatly exacerbated by the downstream disposal of irrigation-generated wastes. Irrigated lands typically generate drainage waters which tend to be laden with salts and residues of the fertilizers and pesticides that are often applied in excess to the irrigated crops. The effect on human health can be very harmful.

If the drainage from the bottom of the root zone percolates downward toward an aquifer, it may gradually contaminate its groundwater, making it unusable for humans even far downstream. In extreme cases, it may even become unsuitable for irrigation. Nitrates as well as chlorides may accumulate in groundwater underlying irrigated lands, to the extent of posing a health hazard to communities relying on wells. Other agents contained in the drainage from irrigated agriculture (as well as from households and industries) are various toxic and carcinogenic elements and compounds from pesticides, such as the element boron (commonly present in detergents), which, even in relatively small concentrations, can be toxic to certain crops.

Where the drainage from irrigated lands is channeled through drainage ditches or pipes and discharged into the river downstream, it pollutes the water there and may make it unusable for people as well as harmful to natural fauna and flora. The alternative to discharging the drainage into the river is to convey it to the sea (which may be quite distant), to lagoons or wetlands (whose fauna, flora, and people may also be vulnerable to the pollutants), to environmentally isolated evaporation basins in the desert, or to very deep aquifers (where the pollutants are diluted)—all of which may be quite expensive to carry out, and perhaps unsustainable in the long run. The Kesterson Reservoir in California is one region where the discharge of drainage from irrigated areas into a wetland has resulted in damage to

wildlife due to the accumulation of water-borne toxic elements (Letey *et al.*, 1986).

III. ONSITE ISSUES

The twin processes of degradation that typically affect irrigated lands in river valleys and low-lying coastal plains are waterlogging and salination. Waterlogging results from the tendency of irrigators to apply a volume of water to the soil in excess of the amount of soil-water taken up by the crop. In arid or semi-arid regions, this is, to some extent, a matter of necessity, to prevent the root zone from accumulating salts. In areas with seasonal heavy rainfall, salts wash out naturally. This is the case in large areas in Southeast Asia where irrigation is used to extend crop production into the dry season.

Application of irrigation adds water-borne salts to the soil. Of course, some sources of irrigation water are saltier than others, but none is entirely salt-free. Moreover, many arid-zone soils contain natural reserves of salts, which are also mobilized by irrigation. Since crop-water uptake typically excludes most salts, the salts left in the root zone tend to accumulate, to the detriment of the crop, unless leached from the soil and driven downward by the extra seepage of water.

In arid and semi-arid regions, this water must be supplied by the irrigation system as well. The balance of water and salts in the root zone, in these regions, is a delicate dynamic process. While the application of too little water will not prevent salt accumulation in the root zone, the application of too much water may be even more insidious. Water flowing downward below the root zone eventually reaches the water table and augments the groundwater, saturating the subsoil. If the water table is very deep and the groundwater has its natural outflow (i.e., it is naturally well drained), the balance of water and salts in the root zone can remain favorable to crop growth. If, however, the water table is shallow and the rate of natural groundwater drainage is slow, the addition of irrigation water from above will cause the water table to rise. Sooner or later (within a few years or decades), the water table approaches the soil surface. The root zone then becomes saturated with water and deprived of oxygen. Since most crop plants require oxygen in the soil for their roots to respire, the saturation of the root zone (a condition called waterlogging) itself restricts crop growth and—in the case of sensitive plants—may cause total crop failure. In areas where such conditions are unavoidable, rice has been the prevalent crop since it has the physiological capability of transmitting oxygen internally from the leaves to the roots.

The process of waterlogging is further exacerbated by soil salination. When the water table comes within about 1 meter (or less) of the surface, a secondary process of capillary rise begins. Instead of percolating downward and leaching away the salts, the salt-laden water (especially where the groundwater is naturally brackish, as is common in arid regions) percolates upward to the soil surface, where it evaporates, leaving the salts behind. So much salt can accumulate at and near the surface that the soil is rendered sterile. In this manner, well-intentioned irrigation projects can, quite inadvertently, induce the salination of originally productive soil.

A further scourge of irrigation is the phenomenon of soil degradation due to sodicity (also called alkalinity), a condition caused by the specific effect of sodium ions adsorbed onto the electrostatically charged clay particles. This, in turn, causes swelling and dispersion of the soil colloids, destroying soil aggregates and restricting the soil's permeability to water and air. When wet, a sodic soil becomes a slick and sticky mud whereas, when dry, its surface hardens to form a dense crust with a typical pattern of cracks. This condition not only reduces the entry of water and air into the soil but also forms a barrier to the emergence of germinating seedlings and to the penetration of their roots.

Sustainability of irrigation is critically dependent on the threat by these onsite processes. Irrigation management systems need to be in place to monitor such processes and a catalogue of preventive steps should be on hand to alleviate the problem early in the process. It is a well-established fact that prevention of these degradation processes is much less costly than their remediation later.

IV. WATER QUANTITY ISSUES

There are objective and subjective reasons why irrigation water is so often applied in excess, i.e., in amounts greater than the actual requirements of the crop. The objective reason, already mentioned, is as a preventive measure to flush out salts that would otherwise accumulate in the root zone to harmful concentrations. The subjective reason for the application of excess water is the universal tendency of humans to assume that if a little of something is good, more must be better. In irrigation, however, too much can be worse than too little, for it not only wastes water but also can cause environmental damage.

The environmental problems occur most readily where a combination of the following conditions prevail: (1) low-lying lands, such as river valleys or coastal zones, with high water table conditions and slow rates of lateral groundwater discharge; (2) fine-textured soils of low permeability and slow

internal drainage; (3) arid regions with high rates of evaporation; (4) brackish water resources (both irrigation water and groundwater); (5) high concentrations of sodium ions in the irrigation water; (6) application of irrigation in excessive quantities without adequate provision for artificial drainage; and (7) inappropriate soil and water management practices that exacerbate soil degradation (e.g., excessive tillage and soil compaction).

Conversely, waterlogging processes can be countered by controlling the application rate of water so as to respond to actual crop requirements in timely fashion, and to provide the fractional extra amount needed for leaching—and no more. This pattern of irrigation should be coupled with the removal of excess water and prevention of water table rise by means of controlled surface-water and groundwater drainage. Where necessary, the addition of chemical amendments (e.g., lime or gypsum) and organic matter can help to protect or restore soil structure and fertility. Alternatively, the land is used for crops that can tolerate waterlogging, primarily rice, where water is not a scarce commodity.

Several factors and processes combine to threaten the future sustainability of irrigation. Water supplies for irrigation are likely to be less readily available and more costly to secure and manage than heretofore, owing to widespread depletion and degradation of water resources. A prime example is the depletion of the Ogallala aquifer in the Southern Great Plains of the United States, resulting from the overdrawing of groundwater (beyond the rate of recharge), which has caused the water table to fall and has made the continued pumping of water increasingly expensive. Another factor is the gradual contamination of groundwater, as well as of surface waters, with residues of salts, fertilizer nutrients, pesticides, domestic sewage, industrial effluent, etc., which may render water useless for irrigation purposes.

In some areas, irrigated agriculture accounts for more than 85% of the consumptive use of water. As trade and the interchange of goods and information become global and the fluctuations of commodity markets come into play, the relative competitive advantages of agricultural production in various regions may accrue in favor of one region, to the detriment of another.

An important factor will be the escalation of energy costs. Energy prices inevitably affect the costs of water since the delivery of water is often energy dependent. As other sectors of the economy compete for this water, agriculture may lose out, with the production gap being filled through trade. In some areas, the rising cost of water makes the continuation of irrigation unprofitable or even prohibitive. In a few cases, notably in the western United States, newly established "water markets" permit cities and industries to purchase the water rights traditionally held by individual farmers or farming corporations.

Irrigation management regimes that make no provision for measuring and calibrating water volume applied to crops, and do not charge farmers for the water in proportion to the quantity used, serve to exacerbate the natural tendency to excess. However, water is becoming increasingly scarce. Needed, therefore, are positive economic inducements toward water conservation, coupled with sound and timely guidance on how to optimize the quantity and scheduling of irrigation.

A. Improving Water Use Efficiency

Since onsite soil degradation often results from the excessive application of irrigation water, the issue of water-use efficiency is important not only from the standpoint of minimizing the cost of the water itself and its delivery to the crop but also from the standpoint of minimizing soil degradation by waterlogging and salination.

Any concept of efficiency is a measure of the output obtainable from a given input. Water-use efficiency in irrigation can be defined in different ways, however, depending on the nature of the inputs and outputs considered. For example, one can define as an economic criterion of efficiency the financial return in relation to the money invested in the installation, operation, and maintenance of a water supply and delivery system. The difficulty is that costs and prices fluctuate from year to year and vary widely from place to place, so they may not be universally comparable.

A widely applicable agronomic expression of efficiency is the *crop water-use efficiency*, commonly defined as the amount of vegetative dry-matter yield per unit volume of irrigation water taken up by the crop from the soil. Because most of the water taken up by plants in the field is transpired (in arid regions, as much as 99%), while generally only a relatively small amount is retained, the crop water-use efficiency is, in effect, the reciprocal of what has long been known as the *transpiration ratio*, defined as the mass of water transpired per unit mass of dry matter produced.

What we refer to as *technical efficiency* is what irrigation engineers call *irrigation efficiency*. It is generally defined as the net amount of water added to the root zone divided by the amount of water taken from some source (Hillel, 1997). As such, this parameter reflects the loss of water incurred during conveyance to the field and in distribution and application in the field, and it can be applied to large regional projects, to individual farms, or even to specific fields.

In practice, many irrigation systems still operate in an inherently inefficient way. In many surface-irrigation schemes, one or a few farms are allocated large flows representing the entire discharge of a lateral canal for a specified period of time. Where water is delivered to the consumer only at

fixed times and charges may be assessed per delivery regardless of the actual amount used, customers tend to take as much water as they can while they can. The often results in overirrigation, which not only wastes water but also causes projectwide and perhaps even regionwide problems connected with the disposal of return flow, leaching of nutrients, restricted aeration of the root zone, and water-table rise requiring expensive drainage to rectify. Although it is difficult to obtain reliable statistics, it has been estimated that the average irrigation efficiency in such schemes is less than 50% and, in some cases, may be as low as 30%. Since, with proper management, irrigation efficiencies of 80 to 90% can actually be achieved, there is obviously need for much improvement.

Particularly difficult to change are management practices that lead to deliberate waste of water, not necessarily because of insurmountable technical problems or lack of knowledge but simply because it appears more convenient or economical in the short run to waste water rather than to apply proper management practices of water conservation. Such situations typically occur where the price of irrigation water is lower than the cost of labor or equipment needed to avoid overirrigation. Very often, the price of water does not reflect its true cost but is kept purposely low by government subsidy, which can be self-defeating in the longer run.

Promoting water-use efficiency requires control of the entire field water balance, including subsoil seepage, surface runoff, and evaporation. In the case of gravity (surface flooding) irrigation systems, it is often virtually impossible to achieve uniform water distribution over the field, especially where the surface topography is not perfectly smooth and the soil properties are not uniform in space nor constant in time, without incurring some runoff. Only where provision is made to collect irrigation and rainfall surpluses at the lower end of an irrigation system and to direct the water as controlled return flow can this water be used productively. Evaporation losses associated with water application include any evaporation from open water surfaces (e.g., from flooded portions of the land), evaporation of water droplets during sprinkling, wind drift of droplets away from the target area, and evaporation from wetted crop canopies or from wet soil during and after each irrigation. Clearly, any method of irrigation that minimizes evaporation is likely to increase the efficiency of water utilization by the crop. Modern irrigation systems (e.g., drip irrigation) that introduce water directly into the root zone without sprinkling the foliage or wetting the entire soil surface can indeed achieve much higher efficiencies than conventional systems.

The one component of the field water balance that generally cannot, and probably should not, be reduced is transpiration by the crop. In the open field (in contrast to artificial enclosures such as greenhouses), little can be done to limit transpiration if the conditions required for high yields

are to be maintained. The greatest promise for increasing water-use efficiency appears to lie in allowing the crop to transpire freely at the climatic limit by preventing or alleviating any possible water stress while avoiding waste and preventing all other environmental constraints to the attainment of the full productive potential of the crop. This is particularly important in the case of the superior varieties that have been developed in recent decades. These varieties achieve their potential yields only if water stress is prevented and other factors such as soil fertility, aeration, and soil tilth are also optimized. Plant diseases and pests, as well as competing weeds and insufficient fertility of the soil, may depress yields without a proportionate decrease in water use. All management practices can thus influence water-use efficiency, and none can be considered in isolation from the others.

V. WATER QUALITY ISSUES

The quality of irrigation water affects soil salinity and sodicity, cation exchange, soil acidity or alkalinity, nutrient availability, clay dispersion or flocculation, and soil structure. The latter, in turn, affects soil–water relations as well as soil aeration. Clearly, therefore, the composition of irrigation water is an important determinant of crop growth and agricultural drainage quality. To avoid the accumulation of salts to toxic levels, their inputs to the soil must not exceed the rate of their removal from the soil or their conversion to unavailable forms within it. The control of soil salinity must therefore include measures to control both the input and the output of salts to and from the root zone.

Solutes are added to the soil solution in irrigation water infiltrated from above, in groundwater rising by capillarity from below, and in the dissolution of salts initially present in solid form within the soil and subsoil. Removal of solutes from the soil includes uptake by plants, downward transport by percolation and drainage (leaching), erosion of the soil surface by overland flow and by wind, precipitation or adsorption onto the solid phase and conversion to insoluble forms, and—for some substances—volatilization of gaseous compounds.

The hazard of plant stress and soil salination posed by irrigation water containing salts of varying composition and concentration depends on soil conditions, climatic conditions, crop species and variety, and the amount and frequency of the irrigation applied. In general, irrigation water with an electric conductivity (EC) lower than 0.7 deciSiemens per meter poses little or no danger to most crops, whereas EC values greater than 3.0 dS/m may restrict the growth of most crops (Ayers and Wescot, 1985).

The salinity of irrigation water is defined as the total sum of dissolved inorganic ions and molecules. The major components of salinity are the cations Ca, Mg, and Na and the anions Cl, SO_4, and HCO_3. The potassium, nitrate, and phosphate ions, however important nutritionally, are usually minor components of soil salinity. In addition, certain constituents (such as boron) may have an important effect on crop growth even though their concentrations are usually too low to have any substantial effect on the soil's total salinity.

Irrigation waters of different sources, locations, and seasons vary greatly in quality. Some irrigation waters contain as little as 50 and others as much as 3000 grams of salts per cubic meter. Since the volume of water applied in irrigation to a crop during its growing season commonly varies between 5000 and 20,000 cubic meters per hectare, the salt input to a crop may thus range between 250 kg and as much as 60,000 kg per hectare. That is a very wide range indeed.

Another important criterion of irrigation water quality is the sodium adsorption ratio (SAR). High alkalinity of irrigation water, manifested when the pH value is above 8.5, generally indicates the predominant presence of sodium ions in the solution and poses a danger of soil sodification. Freshly pumped groundwater may have a high sodium adsorption ratio even if the pH is below 8.5, owing to the presence of dissolved CO_2 (which forms carbonic acid). Samples of such water should be aerated to allow the CO_2 to effervesce prior to measurement of the pH.

With high SAR water, irrigation by sprinkling tends to form a surface seal (crust) under the impact of the drops striking the bare soil. Flood irrigation may also cause the breakdown of soil aggregates by air slaking (Hillel, 1998). On the other hand, application of water by drip irrigation, at spaced points on the surface or below it, may lessen the physical disruption of soil structure that would otherwise take place under the influence of high SAR water.

As a rule, every effort should be made to avoid the use of salt-loaded water for irrigation. However, as river water is reused after it is drained from an irrigation scheme back into the river or groundwater, these bodies of water tend to gain salts, to the detriment of downstream irrigation schemes. In certain circumstances, and with appropriate precautions, available brackish water can be used for the irrigation of salt-tolerant crops. This is especially the case with deep sandy soils, in which drainage is unrestricted and there is little risk of either groundwater rise or of soil salination and sodification.

Various strategies have been proposed for the use of brackish water (including recycled drainage water). One way is to use the water, such as it is, for irrigation. Another way is to blend good-quality water with brackish water so as to extend the water supply (Sinai *et al.*, 1988). A third way is to

alternate the applications of the brackish water with applications of better quality water, where such is available (Grattan and Rhoades, 1990). It appears that the optimal strategy depends on circumstances, i.e., on the answer to the following questions: How saline is the brackish water? How good is the quality of the nonsaline water? How tolerant are the crops to be grown? How sensitive is the soil to physicochemical degradation? How effective is natural rainfall in leaching out the excess salts? And, perhaps most important, what are the long-term environmental consequences of using brackish water for irrigation?

To evaluate the use or reuse potential of water for irrigation, standard water sampling techniques and analysis can be used (Chapman and Pratt, 1982). The most important water quality parameters are electric conductivity (an indicator of total salinity), sodium-adsorption ratio, boron concentration, and the presence and concentration of other potentially toxic elements. Irrigation water that contains more than 5 milligrams per liter of boron can be detrimental to many crops.

The use of brackish water for sprinkling irrigation may cause foliar injury. The degree of injury depends on the concentrations of ions in the water, the sensitivity of the crop at various stages of its growth, the water stress of the crop prior to irrigation, and the frequency of sprinkling. The potential damage also depends on the prevailing environmental conditions, including the temperature and relative humidity of the atmosphere, which affect the rate of evaporation. Sprinkling at night, when atmospheric temperature and evaporativity are relatively low, evidently reduces foliar absorption and injury (Pratt and Suarez, 1990).

In principle, the longer the interval between successive irrigations, the more concentrated the residual solution in the root zone and the more severe the salt stress imposed on the plants. Hence, when the irrigation water is brackish, an appropriate management strategy is to increase the frequency of irrigation so as to maintain a high level of water potential in the root zone. Thanks to its ready adaptability to high-frequency irrigation, drip irrigation beneath the canopy is an appropriate method to use with brackish water, especially as it avoids direct foliar exposure to salinity. In some cases, however, increasing irrigation frequency may also result in the impedance of soil aeration and increased risk of root disease (Gratttan and Rhoades, 1990). These risks are much less likely in coarse-textured (sandy) than in fine-textured (clayey) soils.

Brackish water may also be used in a system of agroforestry. Salt-tolerant trees have the capacity to thrive when irrigated with brackish water, and also have the potential to lower the water table by the extraction and transpiration of water from deeper layers in the soil, thus reducing the volume and expense of drainage needed in an area. Among the trees suitable for this type of agroforestry are certain species of eucalyptus, acacia, casuarinas, poplar,

mesquite, Elderica pine, and tamarisk (Lee, 1990). The harvested wood may be used for fuel, for pulp, or for construction.

A publication issued by the National Research Council (1990) lists and describes scores of salt-tolerant plants, native to various saline areas, that may be capable of utilizing land and water unsuitable for conventional salt-sensitive crops (*glycophytes*). Plants adapted naturally to growing in saline environments, known as *halophytes*, can utilize saline water resources that are generally neglected and are usually considered impediments rather than opportunities for development. However, most undomesticated halophytes display poor agronomic qualities. The possibility of turning some of them into economic crops will require intensified genetic research in the coming decades.

A. Leaching Requirements

One of the principal preventive measures to avoid salt accumulation during repeated cycles of irrigation is to apply water in an amount greater than evapotranspiration so as to deliberately cause a fraction of the water applied to flow downward through the root zone and flush away the excess salts. However, unless the water table is very deep or lateral groundwater flow is very rapid, the extra irrigation can cause a progressive rise of the water table. And, once the water table comes within a meter or two of the soil surface, water tends to seep upwards by capillary action and to reinfuse the soil with salt during the periods between irrigations.

Here, we face a dilemma similar to that of the proverbial frog in the pot of boiling water. To escape being cooked, the frog must leap, but in leaping the frog may fall into the fire and be burned. So the leap must be at just the right trajectory to escape both misfortunes. In our case, we must apply more water to leach out salts, but applying too much water will raise the water table and thus bring back the salts from below. Therefore, the amount of water applied must be optimized so as to allow leaching without water table rise. The desired optimization can seldom be achieved without the installation of artificial groundwater drainage.

In areas where the natural drainage is slow and artificial drainage is not provided, it becomes impossible to sustain irrigation in the long run, and the land must, sooner or later, be abandoned owing to progressive salination. This is indeed happening in great and small river valleys from (to mention just a few examples) the Indus Valley in Punjab (Pakistan and India) to the Murray-Darling Basin in Australia to the San Joaquin Valley in California to the Aral Sea Basin in Uzbekistan, Kazakhstan, and Turkmenistan. The best preventive measure for such salinity-prone areas is the timely installation and continuing operation of artificial drains.

Much attention has been devoted to the assessment of the optimal quantity of water that must be applied to cause leaching. Exaggerated leaching not only wastes water but also tends to remove essential nutrients and to cause waterlogging. The concept of leaching requirement was first developed by the US Salinity Laboratory (Richards, 1954). It has been defined as the fraction of irrigation water that should be percolated out of the bottom of the root zone in order to prevent average soil salinity from rising above some specifiable limit.

According to the standards developed there, the maximum concentration of the soil solution in the root zone, expressed in terms of electrical conductivity, should be kept below 4 deciSiemens per meter for sensitive crops. Salt-tolerant crops like beets, barley, cotton, and alfalfa may give good yields at values of 8 or more dS/m. The problem encountered in any attempt to apply such a simplistic criterion is that, in the field, the concentration of the soil solution varies greatly with space and time. In addition, the sensitivity or tolerance of any crop to salinity depends on its stage of growth and on such variables as ambient temperature, atmospheric humidity, soil matric potential, nutrient availability, and soil aeration, (Hillel, 2000).

As suggested by Nielsen and Biggar (1961), leaching soils at a water content below saturation (e.g., under low-intensity sprinkling or intermittent ponding) can produce a more efficient removal of salts that under continuous flooding. In soils with macropores—cracks, wormholes, or decayed root channels—much of the water may move rapidly down those large passageways while bypassing the greater volume of the soil containing the salt, so it is largely ineffective in leaching the micropores of the soil matrix. Under low-intensity sprinkling, on the other hand, the soil never becomes saturated, so a greater portion of the applied water moves through the soil matrix.

The efficiency of leaching can be defined as the quantity of soluble salts leached per unit volume of water applied (Hoffman, 1985; Keren and Miyamoto, 1990). The inherent spatial variability of soil properties in the field is itself a cause of inefficiency in the leaching process under flooding. When the entire field is flooded uniformly, the inflow rate at each spot depends on the local infiltrability of the soil. (If, for example, a field consists of sections that are clay-rich and other sections that are sandy, the uniform application of water at a rate sufficient to leach the clayey sections will entail excessive percolation through the sandy sections.) Sprinkling irrigation, in contrast, can be adjusted to apply water at a nonuniform rate, adjusted to the properties of the soil at each section. As long as the application rate is lower than the maximal "infiltration capacity" of the soil, the flow inside the soil takes place under unsaturated conditions. Finally, under drip irrigation, the flow pattern in the soil is three-dimensional rather than entirely vertical. Although the soil volume directly under each emitter is leached frequently (or even continuously), salts tend to accumulate over the periphery of the

wetted volumes of the soil. Long-term use of drip irrigation may therefore result in irregularly distributed salt accumulations, affecting the crops to be planted in subsequent years. Where seasonal rainfall is insufficient to leach out such peripheral accumulations, it may be necessary to use portable sprinklers every few years to rid the topsoil of the salts more effectively than is possible using drip irrigation alone.

With modern methods of high-frequency irrigation (Hillel, 1997; Rawlins and Raats, 1975), it is possible to maintain the soil solution in the surface zone at a concentration essentially equal to that of the irrigation water. This zone can be deepened by increasing the volume of water applied. High-frequency irrigation not only lowers the concentration of the soil solution in the upper zone (where most of the roots proliferate) but also keeps the matric potential of soil moisture at a high enough level to prevent stressing the crop.

Control of salinity by leaching is accomplished most readily in permeable soils. A coarse-textured (sandy) soil tends to be naturally permeable. On the other hand, a fine-textured (clayey) soil is only permeable if it is well aggregated. Since aggregation is disrupted in sodic soils, every effort must be made to prevent soil sodification.

B. Soil Amendments and Amelioration

The leaching process is enhanced if the applied water contains a concentration of electrolytes sufficient to reduce swelling and dispersion of the clay fraction in the soil. Where leaching occurs with water of very low salinity, soil permeability can be enhanced by the surface application of a slowly soluble electrolyte source, preferably containing divalent or trivalent cations. Such materials, commonly known as *soil amendments*, can replace exchangeable sodium with flocculation-promoting cations (e.g., calcium or magnesium).

The most common soil amendments for the purpose of improving the structure of sodic soils and enhancing the infiltration of water are gypsum ($CaSO_4.2H_2O$) and calcium chloride dehydrate ($CaCl_2.2H_2O$). Gypsum is generally the preferred soil amendment, thanks to its ready availability in many places and its relatively low cost. It may be derived from mines, or be available as a byproduct of the phosphate fertilizer industry (Keren and Myamoto, 1990).

The solubility of pure gypsum is about 2.15 to 2.63 kg/m^3 (roughly, 25 to 31 milliequivalents per liter), depending somewhat on temperature. Applied gypsum dissolves in the soil solution until its solubility limit is reached or until the supply in the soil is exhausted. When the soil solution is subject to evaporation (i.e., at the soil surface), gypsum may begin to precipitate before

other salts of higher solubility (such as sodium chloride) do. The rate of dissolution of applied gypsum depends on its source and degree of granulation. Industrial gypsum generally dissolves more readily than mined gypsum, which typically contains impurities. The amount of gypsum needed to replace the exchangeable sodium (an amount known as the *gypsum requirement*) obviously depends on the initial exchangeable sodium percentage (ESP), the soil's total cation exchange capacity (CEC), and the depth of the soil layer to be treated effectively (Keren and Miyamoto, 1990). A single treatment may not suffice to reclaim a strongly sodic soil. In many cases, the need to counter sodification demands repeated applications of gypsum along with the continuous or intermittent process of leaching the soil to control salinity.

Some arid-zone soils contain native gypsum in amounts sufficient to protect the soil against sodification. However, the presence of too much readily soluble gypsum in the soil solution adds to the osmotic stress imposed on plants. Moreover, where the gypsum occurs in the form of crystalline lenses inside the soil profile (as it does in some desert soils), the introduction of irrigation may dissolve the mineral and cause soil subsidence. Such subsidence can be so uneven as to turn a field that had been leveled for irrigation into a patchwork of depressions and hummocks, which prevent the efficient distribution of water and hence also thwart crop growth. This is what happened, for example, when irrigation was first introduced in certain desert areas in the Middle East (Hillel, 1994).

Arid-zone soils may also contain precipitated lime ($CaCO_3$) that, upon leaching, may dissolve to provide sufficient calcium to replace the initially adsorbed sodium. The rate of dissolution may be increased by various treatments designed to mobilize the soil's own calcium ions. Among the materials used for such purpose are sulfur and iron-aluminum sulfates, which help to solubilize the lime by its partial conversion to gypsum. Other acidulants that must be oxidized in the soil are pyrites and polysulfides. The process of oxidation depends on soil microbes and on the conditions governing their activity. In any case, the process requires time, as its benefits occur gradually rather than immediately.

C. Drainage Requirements

The term "drainage" can be used in a general sense to denote outflow of water from soil. More specifically, it can serve to describe the artificial removal of excess water or the set of management practices designed to prevent the occurrence of excess water. The removal of free water tending to accumulate over the soil surface by appropriately shaping the land is termed *surface drainage* and is outside the scope of our present discussion. The removal of excess water from within the soil, generally by lowering the

water table or by preventing its rise, is termed *groundwater drainage*, which is an integral aspect of sustainable irrigation management.

Numerous investigations of groundwater flow and drainage have resulted in a very extensive body of literature on this subject. Reference is made particularly to the compendium edited by Skaggs and van Schilfgaarde (1999). The artificial drainage of groundwater is generally carried out by means of *drains*, which may be ditches, pipes, or "mole channels," into which groundwater flows as a result of the hydraulic pressure gradients existing in the soil. The drains themselves are made to direct the excess water, by gravity or by pumping, to the *drainage outlet*, which may be a stream, a lake, an evaporation pond, or the sea. In some places, drainage water may be recycled or reused, for agricultural, industrial, or even residential purposes.

Because drainage water may contain potentially harmful concentrations of salts, fertilizer nutrients, pesticide residues, and various other potentially toxic chemicals as well as biological pathogens, it is not enough to "get rid" of it. A major concern is the eventual consequence of its disposal. Therefore, the first requirement of drainage management is to provide a safe outlet for the effluent. The emphasis on modes of agricultural management that minimize chemical inputs may help to lessen the problem posed by the persistence of some of these chemicals in the environment.

Various theoretical and empirical methods have been proposed for designing the optimal drainage system for different sets of conditions (considering the attributes of the soil, the climatic and hydrological regime, and the crops to be grown). The ranges of depth and spacing generally used for the placement of drains in field practice are listed. In Holland, the country with the most experience in drainage, common criteria for drainage are to provide for the removal of about 7 millimeters of water per day, and to prevent a water-table rise above 0.5 meter from the soil surface. In more arid regions, because of the greater evaporation rate and groundwater salinity, the water table must generally be kept much deeper. In the Imperial Valley of California, for instance, the drain depth ranges from about 1.5 to 3 meters, and the desired water-table depth midway between drains should be at least 1.2 meter. For fine-textured (less readily permeable) soils, the depth should be greater still, especially where the salinity risk is high. Since there is a practical and economic limit to how deep the drains can be placed, it is the density of drain spacing that must be increased in such circumstances.

D. Early Warning Systems

The ultimate preventive measure against waterlogging and salination is the a priori installation of drainage. In most cases, however, irrigation systems are organized and irrigation is begun long before drainage is

installed. Indeed, an irrigation project can often function unimpeded for years, even decades, without artificial drainage. In some cases, the land is so well drained naturally or so well leached by rainfall during the rainy season that irrigation can be continued for a long time. However, far more typically, the process of groundwater rise and salt accumulation proceeds inexorably, so that sooner or later (and much sooner in the case of ill-drained river valleys where most irrigation development takes place), the provision of artificial drainage becomes essential and indispensable.

Granted that a drainage system must be planned in advance, at the outset of an irrigation project, the crucial question is just when to begin implementing the difficult and expensive task of installing drainage. If installed too early, the drainage system may lie unused for some time and therefore be both unnecessary and uneconomical, and it may deteriorate before it becomes functional. On the other hand, if installed after waterlogging and salination have advanced, it may be too late to maintain or restore productivity economically. The expansion of irrigation, which had been a principal thrust of agricultural development for some decades, has lately been offset by the abandonment of older areas due to depletion of groundwater reserves, to waterlogging and salination, or to diversion of water supplies to alternative uses.

All these considerations emphasize the importance of having an early warning system to indicate, before the problem becomes acute, that land degradation is incipient and the need for drainage is imminent. Soil salinity is normally monitored by a combination of soil sampling, soil solution sampling, and various *in situ* devices that measure salinity. Depths of the water table can be monitored by means of observation wells.

Detection and diagnosis of salinity is difficult in the early stages of its occurrence. Visual inspection of crops provides obvious clues to salt stress only after the condition is well advanced. In fact, yields of various crops may be reduced significantly by salinity even when the plants show no visible symptoms. Visual inspection of the soil surface may be misleading. For example, white precipitation formed on the surface of furrow-irrigated or drip-irrigated soil may be due mainly to relatively harmless calcite (calcium carbonate) or gypsum (calcium sulfate) rather than to harmful salt (sodium chloride). Only systematic and objective diagnostic testing, conducted repeatedly or continuously, can provide timely warning of incipient salinity problems before they become severe.

Crop plants suffering salt stress eventually exhibit stunted growth, smaller leaves than normal, and a deep-green color (Rhoades, 1990). Such symptoms occur first in spots rather than uniformly over the entire field. Since factors other than salinity per se (e.g., water stress, disease, nutrient deficiencies, or misapplied pesticides) may produce similar symptoms, visually

observed indications of apparent salinity should be checked by means of appropriate chemical analyses of soil, plant, and water samples.

Detailed procedures for sampling soil, water, and plants so as to monitor salinity were described by Hanson and Grattan (1990). Field and laboratory measurements of salinity were reviewed by Robbins and Wiegand (1990). Methods of measuring exchangeable cations and cation exchange capacity are described in Monograph 9 of the American Society of Agronomy (1986). The presence or absence of native lime and gypsum in the soil should also be considered when making management decisions regarding soil salination and sodification. Procedures for determining the content of these minerals are specified in Nelson (1982) and in Monograph 9 of the American Society of Agronomy (1986). Methods of tissue analysis to determine the salt content of plant parts are given in the book edited by Tanji (1990). A very comprehensive and detailed description of electrical conductivity measurements applicable to soil salinity has been prepared by Rhoades, Chanduvi, and Lesch (1999) and issued by FAO.

One possible way to detect the early appearance of salinity is to place plants that are known to be particularly salt-sensitive at regularly spaced intervals throughout the irrigated area. Such interspersed detector plants may reveal early symptoms of physiological stress, and thus provide a timely warning of problems that are likely to exacerbate and become widespread if left uncontrolled. Salt-affected soils tend to be extremely variable in time and space. Efforts should be made to map out the spatial variability of salinity over the area of concern. This can be done by setting a network of sampling sites. At each site, soil and plant samples can be collected periodically. Ideally, such sites should be equipped with salt sensors. Surface monitoring equipment is now available that can be used to detect and map early signs of soil salinity *in situ* without destructive sampling (Rhoades *et al.*, 1997).

The position of the water table should be monitored carefully and regularly, by means of observation wells and piezometers. Such wells may also be used to sample the groundwater for chemical analysis to determine the composition and concentration of salts in it. Both observation wells and piezometers are vertical tubes (of rigid plastic material or metal), inserted into the soil to a depth well below the water table. The difference is that an observation well is perforated to permit free inflow of groundwater along the length of the tube below the water table. In contrast, a piezometer is a similar tube that is not perforated, so its only opening is at the bottom. As such, a piezometer indicates the hydraulic head (or pressure) of the water at the bottom of the tube, rather than the position of the water table. A set of several piezometers, inserted side-by-side to different depths, can indicate the vertical gradient of the hydraulic head below the water table. The direction

and magnitude of that gradient is indicative of the tendency of the groundwater (and hence of the water table) to rise or fall.

Remote sensing techniques have been developed to monitor the condition of soil and vegetation. One such method is aerial photography. Infrared film can be used to detect salinity-induced plant stress. With this film, dark-green foliage appears bright red; light-green foliage pink; barren saline soil white; and nonsaline soil gray, bluish-gray, or green. The color produced by clear water is a very dark blue, whereas that produced by sediment-laden water is a lighter shade of blue. Thus, clusters of plants and patches of soil affected by salinity can often be readily identified. In some cases, it may be possible to estimate fractional areas that are infected with salinity to different degrees of severity. As the relative degrees of salinity tend to vary from season to season and from one area to another, repeated monitoring by means of infrared photography can help in guiding management practices. Another useful technique for detecting plant water stress caused by soil dryness or salinity is the measurement of canopy and soil temperature, using infrared-emission thermometry.

Where possible, preventive or remediative treatments should be applied preferentially to specifically affected locations, rather than indiscriminately to the whole area. For example, spots affected by sodicity should be given extra doses of soil amendments at the appropriate time. This spatially and temporally targeted approach is likely to be more efficient than the common practice of treating a large area uniformly, and it is consistent with the general trend toward "precision agriculture" guided by modern geographic positioning systems (GPS).

V. HUMAN ASPECTS OF IRRIGATION MANAGEMENT

Irrigation is not merely a mechanical task of delivering water to crops and managing the onsite and offsite consequences. It is a human enterprise and a social function. No consideration of irrigation development and sustainability should fail to note that, ultimately, the success of every irrigation project or district depends on whether and to what degree it contributes to the welfare of its practitioners and to that of the larger community.

The first requirement for the maintenance and improvement of irrigation is that the workers engaged in it be strongly motivated to the task and can expect to be well rewarded for their effort toward its successful attainment. They must also be properly informed, not merely trained in routine operations but enabled to understand the fundamental principles. In addition, they must be allowed the opportunity, and given access to the material

inputs necessary, to exercise initiative toward improving their own performance and that of the system as a whole.

An irrigation scheme should also contribute to human welfare in a larger sense. Many irrigation systems in the developing world are used for nonagricultural purposes as well as for raising crops: domestic water supply, waste disposal, power generation, industry, transportation, fishing, and recreation. Some of these functions may interfere or conflict with the basic functioning of the irrigation project. Unless such potential conflicts are recognized and reconciled, the irrigation system itself will prove unsustainable even if its basic operations are sound.

One of the most serious problems in irrigation projects is the potential health hazard resulting from the use of open water channels for drinking, bathing, washing of clothes, and disposal of waste. It has been said that "wherever water goes, disease follows." Unfortunately, water storage and conveyance facilities present favorable breeding opportunities for disease vectors (such as mosquitoes and snails) and for pathogens. Among the water-borne hazards are schistosomiasis (bilharzias), onchocerciasis (river blindness), malaria, cholera, dysentery, and other intestinal diseases. Public health specialists should therefore participate in the design and operation of irrigation schemes so as to assure their continuing beneficial functioning.

Among the factors that may contribute to the control of water-borne diseases are the following:

1. Concrete lining of the conveyance and drainage channels to prevent stagnation along the banks as well as to reduce seepage loss of water.
2. Control of riparian vegetation within the channels and reservoirs, to prevent clogging, stagnation, and harboring of diseases.
3. Protection of channels from wading animals that may breach the banks and pollute the water.
4. Control of waste disposal by humans, who must be provided with environmentally safe sanitary facilities.
5. Treatment of the water used directly for human needs (by filtration, chlorination, and the use of other parasite controls).

The goals of safe water supply and disposal can be attained most effectively in systems that convey water in closed conduits and restrict access to storage reservoirs.

It can thus be seen that the proper sustainable management of irrigation is a complex and comprehensive undertaking, requiring attention to much more than hydraulics and agronomy. The design and operation of each irrigation project is necessarily site-specific, not only because of variable physical and agronomic conditions. A special combination of human and economic factors exists in each case and must be recognized in any attempt to ensure the viability of irrigation on a continuing basis.

VI. THE PROSPECT OF CLIMATE CHANGE

A factor that may be important in the coming decades, the impacts of which are not yet clear, is the prospect of global warming due to the enhanced atmospheric greenhouse effect. A warmer climate is certain to increase both evaporation and precipitation, i.e., to intensify the entire hydrological cycle. But the manifestation of this change may differ from region to region. The shifting balance between the potential demand for water and the potential supply, both climate-related, is very likely to affect the feasibility and sustainability of irrigation in comparison with rain-fed ("dry-land") farming.

In some areas, the increase of evaporation will exceed the increase of rainfall, so the net effect may be a more arid regime characterized by more frequent and severe periods of drought-induced water deficits, resulting in greater water requirements for irrigation. In other areas, the net effect may be a more humid climate than at present. In either case, there may well be an increase of temporal and spatial variability, which will make crop yields more uncertain. Though the spatial distribution of the expectable changes is extremely difficult to predict accurately, it seems reasonable that the changes will force existing irrigation patterns to adapt in order to remain viable. Warmer conditions may also lead to cropping patterns and practices (e.g., choice of crops and varieties, weed-control and pest-control measures) very different from those now in effect. The necessary adaptation may impose considerable additional costs, such that irrigation may become less sustainable in some areas and more so in others.

VII. CONCLUSION: IRRIGATION IS SUSTAINABLE—AT A COST

The sustainability of irrigation must never be taken for granted. Degradation of soils and depletion of water resources not only caused the collapse of irrigation-based societies in the past, but are threatening the viability of irrigation at present. The problem is global in scope. Decimation of natural ecosystems, deterioration of soil productivity, depletion and pollution of water resources, and conflicts among sectors and states over dwindling supplies and rising demands have become international problems closely linked with irrigation development.

Irrigated agriculture is not an insular industry and cannot be divorced from the overall contexts within which it functions. Those contexts are far from stable. Their dynamics force irrigation to change in response to new

fiscal and political realities even if it seems internally sustainable. Evolving demographics and economies will require the adjustment of water-use patterns for all sectors, including agriculture. Rapidly growing urban centers, along with essential environmental and in-stream uses of water, now compete increasingly with irrigated agriculture for limited supplies of water. Other market forces likely to affect irrigation are changing prices of such essential inputs as seeds, fertilizers, means of pest control, labor, equipment, and other services, as well as energy.

The trends in many places are such that irrigated agriculture will be increasingly difficult to sustain in the future, unless it is able to adapt to changing conditions. Various strategies must come into play if irrigated agriculture is to meet and overcome this challenge (CAST, 1996). One strategy is to alter the crop mix in favor of high-valued fruits, vegetables, and industrial crops (e.g., fiber-producing and biochemical-producing plants). Another strategy is to employ more sophisticated technology and management at the field level. Greater emphasis must be given to efficient water and energy use and to the avoidance of environment degradation. The advent of biotechnology offers the potential for developing crops that can be produced more efficiently, requiring less water and nutrients while yielding products of superior quality. All of these possibilities demand intensive research and development efforts at national and international levels. Public investment in basic and applied research and extension is needed to make the benefits available to all rather than the exclusive property of special interests.

Notwithstanding all of the impending changes, irrigated agriculture is certain to remain an important, indeed an indispensable, component of agricultural production in many arid and semiarid regions. Moreover, it is likely to become even more intensive and efficient. Some measures already available include the conversion of wasteful systems of water conveyance and application to much more efficient ones, such as the use of closed conduits (rather than unlined ditches) and precision application of water in measured response to demand rather than by uncontrolled surface flooding. Among the more efficient systems are drip tubes (placed either on the ground surface or at some depth below the surface) and micro-sprayer technologies, as well as low-energy precision application sprinklers. Surface irrigation can be improved greatly by means of laser-guided land shaping and surge-flow techniques. Further improvements are achieved by multifunctional systems permitting fertilizers and pesticides to be applied with irrigation water. Computerized control systems can improve precision while reducing labor, while remote-sensing techniques (such as infrared monitoring of canopy temperature to detect plant stress) can help tailor treatments to spatially variable field and plant conditions.

Ultimately, the ability of irrigated agriculture to meet future challenges may well depend on the progress of new research to enhance adaptation to

changing conditions—social, economic, and climatic. Such research is itself costly in the short run, but is a wise investment for private, public, national, and international agencies in the long run. Biotechnology is one area of research that seems to hold great promise for improving the yield and quality of crops, as well as their resistance to pests and their tolerance to salinity and drought. However, the genetic manipulation of crops also poses risks to natural ecosystems and must therefore be pursued with great caution.

In the face of the many pervasive problems, we come to the conditional conclusion, supported by practical experience and scientific research, that irrigated agriculture can be sustained, but only if and where certain stringent requirements are met. The requirements are effective prevention of upstream, on-site, and downstream environmental damage. Is society willing to heed those requirements and to bear the costs of ensuring the future sustainability of irrigation, even if that entails larger investments in the present? Stakeholders and policymakers are likely to respond positively only if the long-term environmental processes and their long-term implications are made abundantly clear to all. Although there will be cases where the costs of continuing irrigation may be prohibitive (especially if severe damage has already occurred), in most instances, the cost should be well worth bearing. Investing in the maintenance of irrigation and the integrity of the environment in general can result in improved economic and social well-being. Developing and implementing an effective sustainability program requires an understanding of complex interrelationships with multiple causes, effects, and feedbacks, operating at different scales of space and time.

Irrigated agriculture must strive for a balance between the immediate need to maximize production and the need to ensure continued productivity in the future. It must also strive to achieve a harmonious interaction with the external environment, which includes both natural ecosystems and human enterprises. More specifically, irrigation projects should ensure that water supplies of adequate quality are and will continue to be available, that the salt balance and, hence, the productivity of the land can be maintained, the drainage effluent can be disposed of safely, public health can be safeguarded, and the economic returns can justify the costs. Those requirements are conditioned on an effective program of monitoring and control.

The *sine qua non* of ensuring the sustainability of irrigation is the timely installation and continuous operation of a drainage system to prevent waterlogging and to dispose safely of excess salts. All too often drainage creates off-site problems, beyond the on-site costs of installation and maintenance, since the discharge of briny effluent can degrade the quality of water in its downstream course. Where access to the open sea is feasible, solving the problem is likely to be easier than in closed basins or in areas far from the sea. In those cases, the disposal terminus eventually becomes unfit for human use as well as for wildlife. Hence, the importance of reducing the

volume and salinity of effluents, by such means as improving the efficiency of water use—a task that, in itself, can bring economic and environmental rewards. Much can be achieved by improving the efficiency of water use. Modern irrigation technology offers the opportunity to conserve water by reducing transport and application losses while increasing yields.

The problems posed by the practice of irrigation are real and age-old. In former times, irrigators were largely unaware of, and in many cases, lacked the means to control, the processes of degradation engendered by the application of water to land in arid environments. Now, we know much more about the dynamics of water and salts in the soil–plant–atmosphere continuum, and we have the techniques to prevent what could not be prevented in the past. We have the knowledge, the techniques, and—above all—the imperative.

Irrigated agriculture will not only survive but thrive *in the proper circumstances and with appropriate measures*. In some places, inherently inefficient, self-destructive, and environmentally damaging operations will be forced to terminate. On the whole, however, irrigated agriculture should be able to adapt to the long-term requirements of sustainability and continue to meet the growing needs of humanity in the future, even more than in the past.

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Preface

Volume 88 contains eight timely reviews on topics dealing with biodiversity, carbon sequestration, crop improvement, nitrogen dynamics, and the discipline of soil science. Chapter 1 is a thought-provoking review on the role of biodiversity in agronomy. Discussions are included on the importance of biodiversity to agriculture, soil biodiversity, and climate change and agricultural diversity. Chapter 2 is a comprehensive review on carbon sequestration in subsoil horizons. Topics that are discussed include: sources and dynamics of soil organic carbon in soil profiles, depth distribution of soil organic carbon and roots, and the potential for subsoil organic carbon sequestration. Chapter 3 is a thought-provoking treatise on the present and future status of soil science. Emphasis is placed on the importance of communicating with stake holders and policy makers, basic and applied research, and interdisciplinary collaborations. Chapter 4 covers aspects of nitrogen use efficiency including nitrogen uptake and partitioning, management practices to improve N use efficiency, and plant management. Chapter 5 is a review on forage chicory, a herb used as a forage in livestock production. Topics that are covered include history and breeding, herbage production, grazing management, persistence, nutrient value and animal performance. Chapter 6 deals with pre-sowing seed treatment as a means for improving germination, plant growth and crop yield. Discussions on osmopriming, halopriming, hydropriming, matric priming, thermopriming, priming with plant growth hormones, and other pre-sowing treatments are included. Chapter 7 is a critical review of methodologies for measuring electrical conductivity in soil and soil solutions. Chapter 8 is a thorough review on the role of oxygation in yield potential of crops in oxygen-limited soil environments. Discussions are included on ways to improve soil aeration, oxygation and plant processes, and oxygation scenarios.

I am grateful for the authors' thoughtful and interesting reviews.

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Index

O

P

R

S

T

U

V

W

Contents

The Role of Biodiversity in Agronomy
Daniel Hillel and Cynthia Rosenzweig

The Depth Distribution of Soil Organic Carbon in Relation to Land Use and Management and the Potential of Carbon Sequestration in Subsoil Horizons
Klaus Lorenz and Rattan Lal

SOIL SCIENTISTS IN A CHANGING WORLD

Johan Bouma

Enhancing Nitrogen Use Efficiency in Crop Plants

N. K. Fageria and V. C. Baligar

Forage Chicory (*Cichorium intybus* L.): A Review of Its Agronomy and Animal Production

Guangdi Li and Peter D. Kemp

PRE-SOWING SEED TREATMENT—A SHOTGUN APPROACH TO IMPROVE GERMINATION, PLANT GROWTH, AND CROP YIELD UNDER SALINE AND NON-SALINE CONDITIONS

M. Ashraf and M. R. Foolad

METHODOLOGIES AND THE PRACTICAL ASPECTS OF THE BULK SOIL EC (σ_a)—SOIL SOLUTION EC (σ_w) RELATIONS

Arie Nadler

OXYGATION UNLOCKS YIELD POTENTIALS OF CROPS IN OXYGEN-LIMITED SOIL ENVIRONMENTS

Surya P. Bhattarai, Ninghu Su and David J. Midmore